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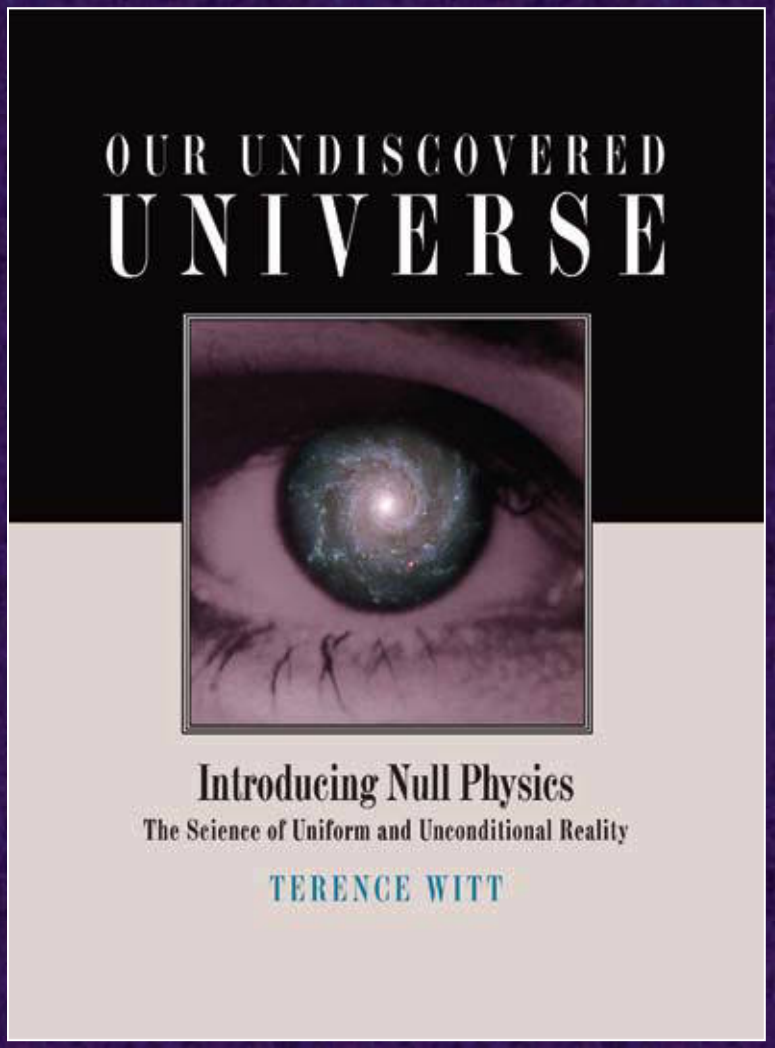

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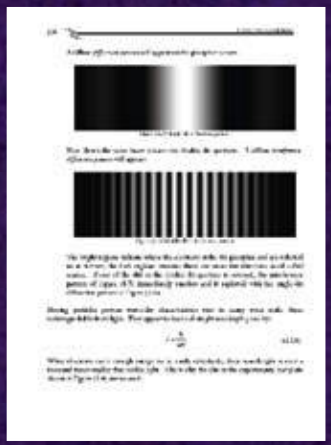

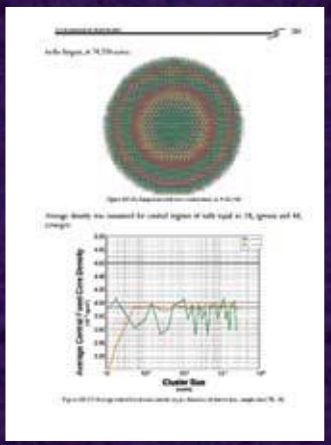

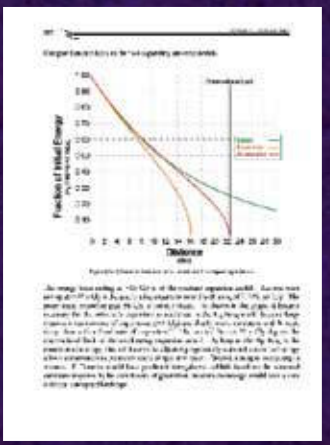

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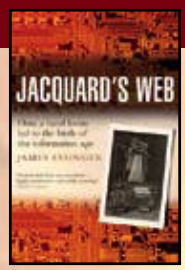

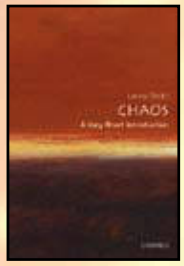

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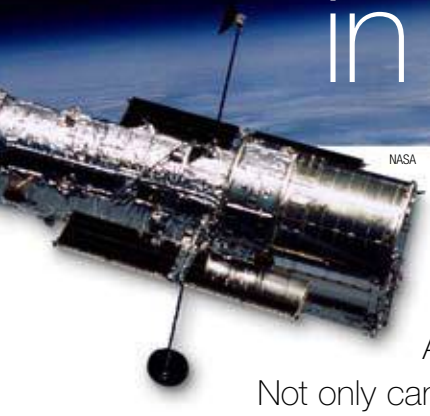


NASA

What is humanity's single greatest achievement? The answer must be specific — if you say "medicine," which drug? If "writing," which work? Astronomers have it a bit easier with this question. Not only can they answer, "the telescope," they can pin down exactly which scope — the Hubble Space Telescope.

Dutch spectacle-maker Hans Lippershey invented the telescope in 1608. The next year, Italian inventor Galileo Galilei pointed it at the sky and began to reveal the universe. He observed sunspots, lunar craters, and Venus' phases. And he saw satellites orbiting Jupiter, indirectly confirming the theory of Polish mathematician Nicolas Copernicus, who placed the Sun — not Earth — at our solar system's center. For more than 2 centuries, each telescope after Galileo's improved the view and added some knowledge.

In 1840, American photographer John W. Draper used the new technology of photography to capture the first celestial image — one of the Moon. Photography, which could record much more detail than the eye could see, expanded humanity's cosmic vision a million-fold.

Chemists developed spectroscopy — the breaking down of light to study an object's composition — at about the same time photography emerged. It didn't take astronomers long to use this new field to explore stellar chemistry, determine how stars shine, reveal unseen companions around stars, and even to measure the universe's expansion rate.

Within the lifetime of *Astronomy* magazine (which began in 1973), two advances have again revolutionized the field. Electronic charge-coupled-device (CCD) detectors replaced film. CCD cameras represent a 20-fold sensitivity gain over even the best photographic emulsions. And by electronically combining digital images, astronomers can remove atmospheric effects, overcome tracking errors, and even correct light pollution's deleterious effect.

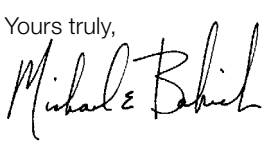
Secondly, all professional telescopes (and the majority of amateur scopes) now operate by computer control. Gone are the days when an observer had to sit staring through a guide telescope, carefully re-centering the target to make up for irregularities in the telescope's drive.

Take all of these advances, and combine them into one telescope. Add detectors to image infrared and ultraviolet radiation. Then, place the instrument above Earth's atmosphere and our planet's day-night cycle. Astronomers' decision to build a space telescope should never be understated. Hubble's position gives it a tremendous advantage over earthbound telescopes, notwithstanding the difficulties involved in servicing it.

Mission engineers also thought ahead — they designed Hubble to be upgradable. Its modular design allowed several teams of space shuttle astronauts to replace Hubble's instruments, gyroscopes, and even its energy-producing solar panels. And every servicing mission resulted in improved performance, new discoveries, and better pictures.

As you turn the page and start examining the universe through Hubble's eyes, prepare for sights Galileo could not even have dreamed about. Hubble's 17-year success story has made it a household word and a pop-culture reference. Besides being the greatest telescope ever built, Hubble may be the single greatest technological achievement of all time. For it not only influenced scores of astronomers, but a generation of everyday folk as well. Because of Hubble's greatest pictures, millions of people consistently turn their thoughts heavenward and contemplate the universe's beauty and unimaginable vastness.

Yours truly,



Michael E. Bakich

COLLECTOR'S EDITION – 2008

HUBBLE'S GREATEST PICTURES

by Michael E. Bakich

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contents

COVER IMAGE: NASA/ESA/N. SMITH (UNIV. OF CALIFORNIA, BERKELEY)/THE HUBBLE HERITAGE TEAM (STScI/AURA); CTIO IMAGE: N. SMITH (UNIV. OF CALIFORNIA, BERKELEY)/NOAO/AURA/NSF

04 EDITOR'S PAGE
The great eye in the sky

PHOTO FEATURES

14 CRUCIBLE OF STAR BIRTH: the Eta Carinae Nebula
28 RAISING THE BAR: spiral galaxy NGC 1300
42 CLOUDY CLUSTER: open star cluster NGC 346
52 THE CRASH OF CREATION: the Whirlpool Galaxy
70 CELESTIAL FIREWORKS: the Crab Nebula
86 RING IN THE NEW: supernova remnant Cassiopeia A
96 BURSTING ON THE SCENE: the Cigar Galaxy

FEATURES

06 HUBBLE IN-DEPTH
The vision thing
For decades, astronomers dreamed of a telescope in space. With Hubble, those dreams came true.

16 SOLAR SYSTEM
Neighborhood watch
Hubble captured a comet collision, tracked planetary storms, and charted the outer solar system.

30 STARS
Great balls of fire
Some stars are quiet, some catastrophically violent, and some harbor hidden planets.

44 STAR CLUSTERS
A thousand points of light
Star clusters paint a picture of star formation by the numbers.

54 NUTS AND BOLTS
Inside the Hubble Space Telescope
Take a look "under the hood" at one of astronomy's most important tools. By Francis Reddy

56 NEBULAE
Cradle to grave
The universe's most beautiful objects show us how stars are born and how they die.

72 GALAXIES
Cities of the universe
Hubble's observations help unravel how galaxies form, evolve, move through space, and collide.

88 COSMOLOGY
To the edge of space and time
Hubble has looked to the distant past to tell us what our future holds.

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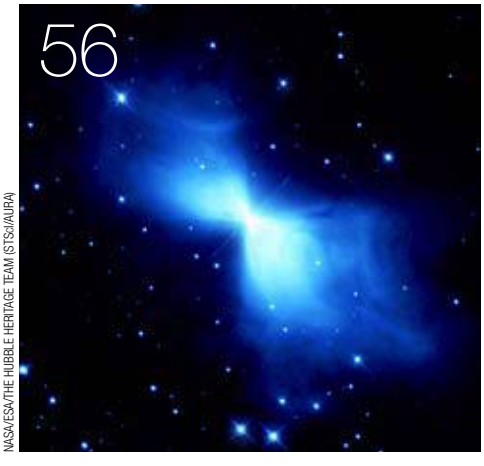


NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

The vision thing

▲ **THE HUBBLE** Space Telescope measures 43.5 feet (13.2m) long with a maximum diameter of 14 feet (4.2m). The spacecraft weighs — on Earth — 24,500 pounds (11,110 kg). NASA

For decades, astronomers dreamed of a telescope in space. With Hubble, those dreams came true.

Long before humanity could blast into space, astronomers dreamed of placing a telescope above Earth's obscuring atmosphere. In 1923, German scientist Hermann Oberth proposed a space observatory. Early balloon-, rocket-, and even satellite-borne instruments produced enough scientific revelations to hint at how much could be accomplished from high-altitude and orbital platforms.

In 1946, American physicist Lyman Spitzer (1914–1997) wrote a paper entitled "Astronomical Advantages of an Extra-terrestrial Observatory." In it, he

outlined the advantages of a space-based observatory. Throughout his career, Spitzer pushed for a space telescope. In 1965, he headed a committee that outlined such an instrument's scientific objective.

In 1962, just 4 years after Congress established the National Aeronautics and Space Administration (NASA), a National Academy of Sciences (NAS) study group recommended the development of a large space telescope. The NAS saw this as a long-range goal of the fledgling space program.

NASA launched its first two successful satellites designed to observe the stars in 1968 and 1972. These Orbiting Astronomical Observatories produced a wealth of information, and support for a more powerful space telescope grew. The space shuttle, with its capacity to deliver and service large payloads, made the space-telescope concept feasible.

NASA selected a team of scientists in 1973 to establish the basic design of such a telescope and its instruments. Funding issues cut the project's scale, and the proposed mirror diameter fell from 118 to 94.5 inches (3 to 2.4 meters). Budget concerns also prompted collaboration with the European Space Agency (ESA), which became involved with the project in 1975. ESA agreed to supply some of the space telescope's instruments as well as the solar panels to power the spacecraft. In return, NASA guaranteed European astronomers at least 15 percent of the telescope's observing time.

NASA assigned responsibility for the design, development, and construction of the space telescope to the Marshall Space Flight Center in Huntsville, Alabama. Goddard Space Flight Center in Greenbelt, Maryland, developed the scientific instruments and became the ground-control center.

Construction and assembly of the space telescope was a painstaking process that spanned almost a decade. Contractors finished the precision-ground mirror in 1981 and the optical assembly in 1984. The science instruments arrived at NASA in 1983. In 1985, engineers completed assembly of the entire spacecraft. NASA originally scheduled launch for 1986 but delayed it after the Challenger accident. Finally, space shuttle Discovery (STS-31) carried Hubble into space April 24, 1990.

What's in a name?

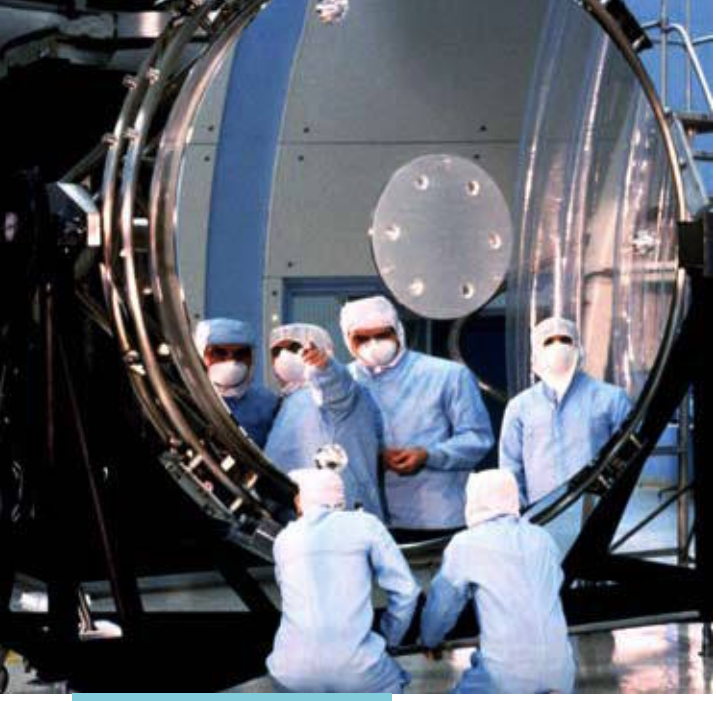
When NASA had secured funding for the space telescope, the agency decided to name it after American astronomer Edwin Powell Hubble (1889–1953). Hubble was an apt honoree because his studies expanded the universe beyond our Milky Way.

Using the 100-inch reflector at Mount Wilson Observatory in California, Hubble conclusively proved spiral "nebulae" lay much farther away than previously thought. In essence, they were galaxies like the Milky Way.

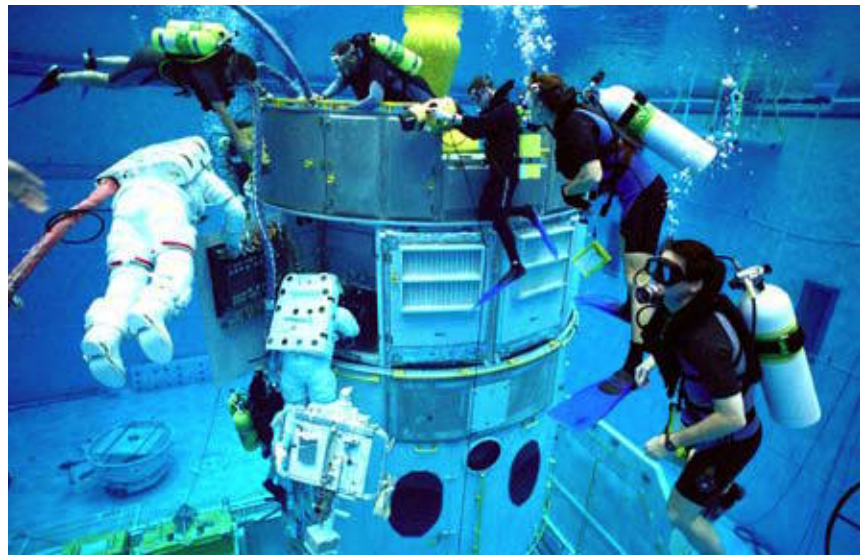
Hubble, along with American astronomer Milton L. Humason (1891–1972), also discovered galaxies' distances are proportional to their redshifts (which reveal the speeds at which the galaxies are moving away from us). Now known as Hubble's law, this relationship marked the first observational support for the Big Bang theory.

The space telescope named for Hubble is part of NASA's Great Observatories series, a quartet of space-based telescopes. The other three instruments are the Compton Gamma Ray Observatory, the Chandra X-ray Observatory, and the Spitzer Space Telescope.

▲ **A CRANE** lifts Hubble into the upright position at Kennedy Space Center in preparation for its 1990 launch aboard space shuttle Discovery (STS-31). A close look at this image reveals a portion of the 225 feet (68.6m) of handrails installed around the outside of Hubble for astronauts to grip during repair-mission spacewalks. NASA



▲ **HUBBLE'S** primary mirror measures 94.5 inches (2.4m) in diameter. Here, workers inspect it prior to placing it in the telescope's frame. When light enters Hubble, it reflects off this mirror and strikes a second, smaller mirror. The light reflects again, this time through a two-foot (0.6m) hole in the center of the primary mirror. There, Hubble's instruments wait to capture it. In this photo, the hole is covered. NASA



▲ **TO SERVICE HUBBLE,** astronauts train in a huge, water-filled tank that simulates weightlessness. The 40-foot-deep (12m) tank at NASA's Johnson Space Center contains full-scale underwater mockups of Hubble, its instruments, and the carriers that hold the instruments. Underwater, the astronauts wear pressurized suits similar to their spacesuits. NASA

Construction and engineering

Once the space-telescope project had been given the go-ahead, Marshall Space Flight Center took responsibility for the design, development, and construction of the telescope. Goddard Space Flight Center assumed control of the scientific instruments and became the mission's ground-control center. Optics company Perkin-Elmer designed and built the optical assembly and Fine Guidance Sensors. Lockheed constructed the spacecraft.

The mirror and optical systems were the most crucial parts. Telescopes typically have mirrors polished to an accuracy of about 1/10 the wavelength of visible light. Because Hubble would observe from near-ultraviolet to near-infrared, its mirror needed to be polished to an accuracy twice as good.

Hubble contains a 94.5-inch (2.4m), f/24 mirror in a Ritchey-Chrétien telescope design. The wavelengths Hubble can "see" range from 115 to 1,000 nanometers (visible light's range is 400 to 700 nm).

The spacecraft itself was another major engineering challenge. It would have to withstand frequent passages from direct sunlight into Earth's shadow (once each 97-minute orbit), which would generate major temperature changes. A shroud of multi-layered insulation surrounds a light aluminum shell, where the telescope and instruments sit, and keeps the temperature stable. Within the shell, a graphite-epoxy frame keeps the telescope aligned.

FAST FACTS

Using Hubble:

- Anyone can apply for time on the telescope; there are no restrictions on nationality or academic affiliation. Competition for the time, however, is intense. Less than 20 percent of requests meet approval.
- Astronomers awarded 13 amateur astronomers time on Hubble between 1990 and 1997. Since 1997, however, budget cuts have prevented NASA from approving amateurs' requests.
- Scheduling observations for Hubble is not simple. Because of the craft's low Earth orbit allowing the space shuttle to reach it for servicing missions, most astronomical targets are hidden by Earth for nearly half of each orbit.

Cost:

- Hubble's original total cost estimate was $400 million, but the telescope actually cost more than $2 billion to construct. The craft's cumulative costs through 1999 stand at between $4.5 and $6 billion for the United States and 593 million Euros ($800 million) for Europe.

Size:

- Length: 43.5 feet (13.2m)
- Weight: 24,500 pounds (11,110 kg)
- Maximum diameter: 14 feet (4.2m)
- The only restriction on Hubble's size was that it had to fit inside the space shuttle's cargo bay.

— Continued on page 10

WORKING TOWARD A SPACE TELESCOPE

November 20, 1889
American astronomer Edwin Powell Hubble was born in Marshfield, Missouri.

1923
German rocket scientist Herman Oberth speculated about telescopes in orbit in his book *Die Rakete zu den Planeträumen* (The Rocket to Interplanetary Space).

January 1, 1925
Hubble announces his observations of nebulae with the 100-inch Hooker Telescope on Mount Wilson in California. He proves they are separate galaxies, and not part of the Milky Way.

Operations

In 1981, the Space Telescope Science Institute (STScI) began operation. The Association of Universities for Research in Astronomy (AURA) runs STScI, which resides in Baltimore. The institute sits on the Homewood campus of Johns Hopkins University, one of the 32 American universities and seven international affiliates that make up AURA.

STScI is responsible for the scientific operation of the telescope and delivery of data to astronomers. Two groups provide engineering support: NASA, and contractors at Goddard Space Flight Center, 30 miles south of STScI. Four teams of flight controllers — Hubble's Flight Operations Team — monitor Hubble's operation around the clock.

Hubble operated in three distinct phases. During the first phase of the mission, Orbital Verification (OV), Marshall Space Center had responsibility for the spacecraft. OV consisted of an extended, 8-month spacecraft check, including tests of the onboard computers, pointing control system, and solar arrays.

Next came the Science Verification (SV) phase, lasting nearly another year. Engineers tested each of the six science instruments to verify their capabilities and set limits on their safe operations during the mission. Goddard Space Flight Center maintained responsibility for the spacecraft during SV.

The last phase, known as the General Observer (GO) phase, was to last from the end of SV through the end of the mission and was the responsibility of STScI. However, mission scientists included some general observations during the SV phase because the OV and SV portions of the mission lasted longer than engineers expected.

Hubble's instruments

When launched, Hubble carried five scientific instruments (All have been replaced since then). The Wide Field and Planetary Camera (WFPC) was a high-resolution imaging device primarily intended for optical observations. It incorporated a set of 48 filters isolating particular spectral lines. WFPC contained four charge-coupled device (CCD) chips, three of which were wide-field chips, while the fourth was the planetary camera. This last chip had a greater magnification than the other three.

The Goddard High Resolution Spectrograph (GHRS) operated in the ultraviolet. Also optimized for ultraviolet observations were the Faint Object Camera (FOC) and the Faint Object Spectrograph (FOS). These two instruments had the highest spatial resolution of any on Hubble. Rather than CCDs, these three instruments used photon-counting detectors.

The final instrument was the High Speed Photometer. It conducted visible and ultraviolet observations of variable stars and other astronomical objects that varied in brightness. It could take up to 100,000 measurements per second with a photometric accuracy of about 2 percent.

Astronomers also could use Hubble's guidance system as a scientific instrument. Its three Fine Guidance Sensors primarily keep the telescope accurately pointed during an observation. They also can carry out accurate astrometry; scientists have confirmed measurements to within 0.00000008°.

Hubble stores data initially on the spacecraft. When launched, the storage facilities were old-fashioned reel-to-reel tape recorders, but astronauts replaced them with solid-state data-storage facilities during servicing missions 2 and 3A. From the onboard storage facilities, data arrive at the ground via the Tracking and Data Relay Satellite System (TDRSS), satellites in low Earth orbit designed to communicate with mission-control facilities. Hubble data first go to the TDRSS ground station and then on to the Goddard Space Flight Center for archiving.

AS THE THIRD repair mission wrapped up, ground controllers sent commands to the telescope while monitoring data from Hubble to check that it continued to function correctly. This picture, taken in 1999, shows the Space Telescope Operations Center at NASA's Goddard Space Flight Center in Greenbelt, Maryland, which controls operations for Hubble. The Space Telescope Science Institute control room in Baltimore has been closed. NASA

1946
American physicist Lyman Spitzer (1914–1997) details the advantages of orbital observations and proposes a space telescope.

1969
The National Academy of Sciences gives its approval for the Large Space Telescope project.

1977
The United States Congress approves funding for a space telescope that NASA names in honor of Edwin Hubble.

1981
The Space Telescope Science Institute begins operations in Baltimore, Maryland.

1984
Space Telescope-European Coordinating Facility begins operations in Munich.

FAST FACTS

— *Continued from page 8*

Spaceflight:

- Orbital altitude: 353 miles (569 km), but this varies
- Orbital inclination: 28.5° to Earth's equator
- Orbital period: 97 minutes
- Orbital speed: 17,500 mph (28,000 km/h)
- Mileage: In its first 16 years, Hubble made nearly 93,500 trips around our planet, racking up almost 2.4 billion miles (3.9 billion km). That mileage equals slightly more than a round-trip to Saturn.

Optical capabilities:

- Hubble cannot observe the Sun or Mercury. Sunlight is so bright it would damage Hubble's sensitive detectors.
- First image: May 20, 1990 (star cluster NGC 3532)
- Hubble's most frequently observed celestial object is Earth. Engineers observe Earth regularly to calibrate all imaging equipment. Images from these "test" observations show no detail.

Power needs:

- Energy source: the Sun
- Energy collecting mechanism: two 24.6-foot-long (7.5m) solar panels
- Power usage: 2,800 watts — On average, Hubble uses the same amount of energy as twenty-eight 100-watt lightbulbs.

Pointing accuracy:

- The telescope can lock onto a target without deviating more than $^{7}/_{1,000}$ of an arcsecond, or about the width of a human hair seen at a distance of 1 mile (1.6 km).

— *Continued on page 12*

◄ **LIFTOFF** for space shuttle Discovery (STS-31) occurred April 24, 1990, at 8:34 A.M. EDT, from Pad 39A. Discovery carried a five-member crew and the Hubble Space Telescope. NASA

Engineers gave Hubble's instruments a modular design. They made it possible for shuttle missions to replace faulty or obsolete parts. Two of Hubble's most important instruments are its gyros and its solar panels.

Hubble uses four of six gyros, or reaction wheels, to control maneuvering. The gyros provide coarse point-and-track control for imaging. Hubble's Fine Guidance Sensors lock onto guide stars to increase pointing accuracy.

Power for the scientific instruments comes from two solar panels that measure 7.9 by 39.7 feet (2.4 by 12.1m). The power generated by these arrays also charges six nickel-hydrogen batteries, which provide power during the roughly 25 minutes per orbit when Hubble lies within Earth's shadow.

Hubble has a problem

On June 25, 1990, the images returned showed a serious problem with the optical system. Although the first images appeared sharper than ground-based images, the optics failed to achieve a sharp focus, and image quality was much lower than expected. Images of point sources spread out more than 10 times what had been specified in the design criteria.

Analysis of the flawed images revealed the problem: The primary mirror had been ground to the wrong shape — it was too flat at the edges. The mirror was barely 2 micrometers off, but the difference introduced severe spherical aberration, a flaw in which light reflecting off the edge of a mirror focuses to a different point from the light reflecting off its center. A commission found the corrector used by Perkin-Elmer had been calibrated improperly.

The flaw meant Hubble could obtain images about as good as those returned by large ground-based telescopes on a night of good seeing. Mission scientists immediately began to seek potential solutions to the problem that could be applied at the first servicing mission, scheduled for 1993.

▲ **AN ASTRONAUT** removes the High Resolution Spectrograph (HRS) during the second servicing mission, in 1997. A new instrument — the Space Telescope Imaging Spectrograph (STIS) replaced the HRS. The telescope can hold four telephone-booth sized instruments and four piano-sized instruments. Spectrographs break incoming light up into its various parts and record the result so astronomers can analyze the chemical and physical properties of the object that produced it. NASA

April 24, 1990
Space shuttle Discovery carries the Hubble Telescope into orbit in mission STS-31.

April 25, 1990
Hubble Space Telescope deployed from space shuttle Discovery.

May 20, 1990
Hubble images its first celestial object, open star cluster NGC 3532 in Carina.

June 25, 1990
Astronomers discover spherical aberration in Hubble's primary mirror.

Late 1990
NASA approves an optical fix, the Corrective Optics Space Telescope Axial Replacement (COSTAR).

Improving Hubble's eye

The fact that the mirror had been ground so precisely to the wrong shape led to the design of new optical components with exactly the same error but reversed. Engineers designed a system to correct the spherical aberration for light focused at the FOC, FOS, and GHRS. The Corrective Optics Space Telescope Axial Replacement (COSTAR) consisted of two mirrors in the light path, one figured to correct the aberration. To fit the COSTAR system onto Hubble, astronauts had to remove the High Speed Photometer.

During Hubble's first 3 years, before COSTAR could be fitted, the telescope still carried out a large number of spectroscopic observations. Despite the apparent setback, this period saw numerous scientific advances as astronomers worked to optimize results.

NASA had originally planned for Hubble to be regularly serviced, but after the mirror problem came to light, the first servicing mission assumed much greater importance. The astronauts would have to work extensively on the telescope to install the corrective optics. Astronauts flew the shuttle Endeavor (STS-61) in December 1993 to install several instruments and other equipment during a 10-day mission.

The crew made two important modifications: COSTAR, which took the physical space occupied by the High Speed Photometer, optimized Hubble's imaging capability; and the Wide Field and Planetary Camera 2 (WFPC2) replaced the original WFPC.

More service with a smile

During Servicing Mission 2 (space shuttle Discovery [STS-82]) in February 1997, astronauts replaced the GHRS and the FOS with the Space Telescope Imaging Spectrograph (STIS) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). They also replaced an Engineering and Science Tape Recorder with a new Solid State Recorder, repaired thermal insulation, and boosted Hubble's orbit.

Space shuttle Discovery (STS-103) flew servicing Mission 3A in December 1999. Astronauts replaced all six gyroscopes (one had failed and rendered the telescope unusable just weeks before the mission), replaced a Fine Guidance Sensor, installed a device to prevent battery overcharging, and replaced thermal-insulation blankets.

Servicing Mission 3B (space shuttle Columbia [STS-109]) in March 2002 saw the installation of a new instrument: The FOC was out, and the Advanced Camera for Surveys (ACS) was in. During this mission, astronauts revived NICMOS, which had run out of coolant in 1999. They replaced the solar arrays for a third time. The new arrays were two-thirds the size of the old arrays, resulting in less atmospheric drag and 30 percent more power.

▲ **WHAT A DIFFERENCE** a corrector lens makes. Hubble first imaged spiral galaxy M100 (left) with the Wide Field and Planetary Camera (WFPC) prior to the first servicing mission. The image is unfocused and shows little detail. During the first servicing mission, in December 1993, astronauts replaced WFPC with the Wide Field and Planetary Camera 2. The new device incorporates a lens array that corrects for the aberration in Hubble's primary mirror. The result (right), taken December 31, 1993, shows a much-improved view. NASA/STScI

▼ **STS-103 ASTRONAUTS** Steven L. Smith and John M. Grunsfeld appear as small figures in this wide-field photograph during extravehicular activity in December 1999. On this spacewalk, they are replacing gyroscopes contained in rate-sensor units inside Hubble. A wide expanse of water, partially covered by clouds, provides the backdrop for the photograph. NASA

December 2, 1993
The launch of STS-61, space shuttle Endeavour, marks the first servicing mission (SM1).

December 7, 1993
Shuttle astronauts replace the Wide Field Planetary Camera (WFPC) with the Wide Field Planetary Camera 2 (WFPC2).

December 8, 1993
Shuttle astronauts install COSTAR, which replaces Hubble's High Speed Photometer.

August 23, 1996
Hubble has traveled 1 billion miles since astronauts placed it in orbit.

February 11, 1997 ►
The launch of STS-82, space shuttle Discovery, marks the second servicing mission (SM2).

FAST FACTS

— Continued from page 10

Hubble's mirrors:

- Primary mirror
  Diameter: 94.5 inches (2.4m)
  Weight: 1,825 pounds (828 kg)
- Secondary mirror
  Diameter: 12 inches (0.3m)
  Weight: 27.4 pounds (12.3 kg)
- Hubble's two mirrors do not deviate from a perfect curve by more than 1/800,000 of an inch. If Hubble's primary mirror were scaled up to Earth's diameter, the biggest bump would be only 6 inches tall.

Power storage:

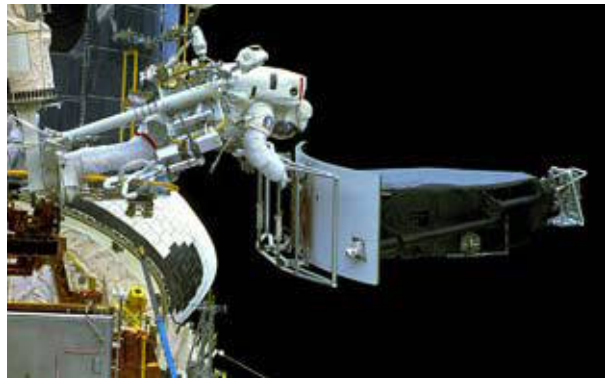
- Batteries: 6 nickel-hydrogen (NiH)
- Storage capacity: approximately equal to 20 car batteries

Data management:

- Hubble transmits about 120 gigabytes of science data every week. That's equal to about 3,600 feet (1,097m) of books on a shelf. Ground control stores pictures and data on magneto-optical disks.
- As of June 30, 2006, the Hubble Data Archive contained more than 790,000 scientific and calibration observations, or 28.3 terabytes of data.
- More than 4,000 astronomers around the world have used Hubble to study the universe.
- The Hubble Data Archive has a request rate that exceeds the daily ingest rate by a 4-to-1 ratio.
- Hubble has provided data for more than 6,300 research papers in the refereed scientific literature; 651 of these papers — an all-time high — were published in 2005.

The death of Hubble

Hubble uses gyroscopes for stabilization and pointing. Normally, three of the six gyroscopes operate. Observations are possible with two gyros, but the area of sky Hubble can view is restricted, and pointing becomes less precise. On August 31, 2005, NASA switched to two-gyroscope mode for regular operations to extend the mission's lifetime. This left the craft with two gyroscopes in use and two on backup. Engineers estimated Hubble may be down to one gyro by 2008, after which time the telescope may become unusable.



THE FIRST servicing mission in 1993 saw astronauts remove the Wide Field and Planetary Camera to replace it with its more powerful successor, the Wide Field and Planetary Camera 2. The camera, shaped something like a grand piano, weighs 610 pounds (277 kg) on Earth. It can detect stars a billion times fainter than the ones we see with our unaided eyes. Hubble took many of its most popular pictures with this second camera. NASA

Another problem is Hubble's location. The space telescope orbits Earth in the tenuous upper atmosphere, and, over time, its orbit decays due to drag. If it is not re-boosted by a shuttle, it will re-enter Earth's atmosphere sometime between 2010 and 2032. The exact date depends on solar activity. The state of Hubble's gyros also impacts the re-entry date — if NASA can control the spacecraft, that minimizes atmospheric drag.

Hubble must be under control when it reenters Earth's atmosphere. Not all of the telescope would burn up on reentry. Parts of the main mirror and its support structure would reach the surface. This scenario creates the potential for damage and even human fatalities. NASA is investigating adding an external propulsion module to Hubble to allow controlled re-entry.

NASA planned for space shuttle Columbia to visit Hubble in February 2005. The tasks of this servicing mission included replacing a Fine Guidance Sensor and two broken gyroscopes, replacing the Wide Field and Planetary Camera 2 with a new Wide Field Camera 3, and installing a new instrument — the Cosmic Origins Spectrograph (COS). However, in light of the Columbia disaster, then-NASA Administrator Sean O'Keefe decided that, for astronaut safety, all shuttles must be able to reach the International Space Station (ISS) should an in-flight problem develop. The shuttle cannot reach both Hubble and ISS during the same mission, and so NASA canceled future manned servicing missions to the telescope.

Astronomers and the public at large assailed this decision. Most think Hubble is valuable enough to merit the risks. Its successor, the James Webb Space Telescope (JWST) will not be ready until well after the 2010 deadline when NASA plans to stop shuttle flights. Also, Hubble can image in infrared, visual, and ultraviolet wavelengths. JWST cannot. It operates solely as an infrared telescope. Because of the furor, on January 29, 2004, O'Keefe said he would review his decision to cancel Hubble's final servicing mission.

February 14, 1997
Shuttle astronauts install the Space Telescope Imaging Spectrograph (STIS) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS).

October 29, 1998
Space Shuttle Discovery (STS-95) launches for the Hubble Space Telescope Orbiting Systems Test (HOST). This mission tested new technologies for installation into Hubble during servicing missions 3A and 3B.

July 13, 1999
After 9 years and 80 days, Hubble flies its 50,000th orbit.

November 13, 1999
NASA places Hubble in safe mode after the failure of a fourth gyroscope.

December 19, 1999
Space Shuttle Discovery (STS-103) launches for the third servicing mission (SM3A).

Resurrection

On July 13, 2004, an official panel from the National Academy of Sciences recommended that Hubble be preserved despite the apparent risks. The report urged, "NASA should take no actions that would preclude a space shuttle servicing mission to the Hubble Space Telescope."

The arrival, in April 2005, of a new NASA Administrator — Michael Griffin — changed the status of Hubble's possible future rescue missions. Soon after his appointment, Griffin authorized NASA's Goddard Space Flight Center to prepare for a manned Hubble maintenance flight, saying he would make the final decision on this flight after the next two shuttle missions, both of which were successes.

On October 31, 2006, Griffin gave the next Hubble servicing mission the final go-ahead. If all continues to go well, Hubble will be serviced by shuttle mission STS-125, currently scheduled to send space shuttle Discovery to the telescope sometime in 2008. During the 11-day mission, astronauts will install fresh batteries, fix the guidance system, and install Wide Field Camera 3 and the Cosmic Origin Spectrograph.

▲ **DURING SERVICING** mission 3A, in December 1999, astronauts C. Michael Foale, left, and Claude Nicollier (on Discovery's robotic arm) installed a Fine Guidance Sensor into a protective enclosure in the shuttle's payload bay. Foale and Nicollier performed the second of three spacewalks to service the Hubble Space Telescope on the STS-103 mission. A large-format camera inside Discovery's cabin recorded this high-resolution image, with ocean and clouds below. NASA

► **THE SHUTTLE'S** electronic still camera (ESC) shows Hubble at 19h47m22s UT December 21, 1999. The telescope was berthed securely in Discovery's (STS-103) payload bay soon after astronauts captured it during Servicing Mission 3A. NASA

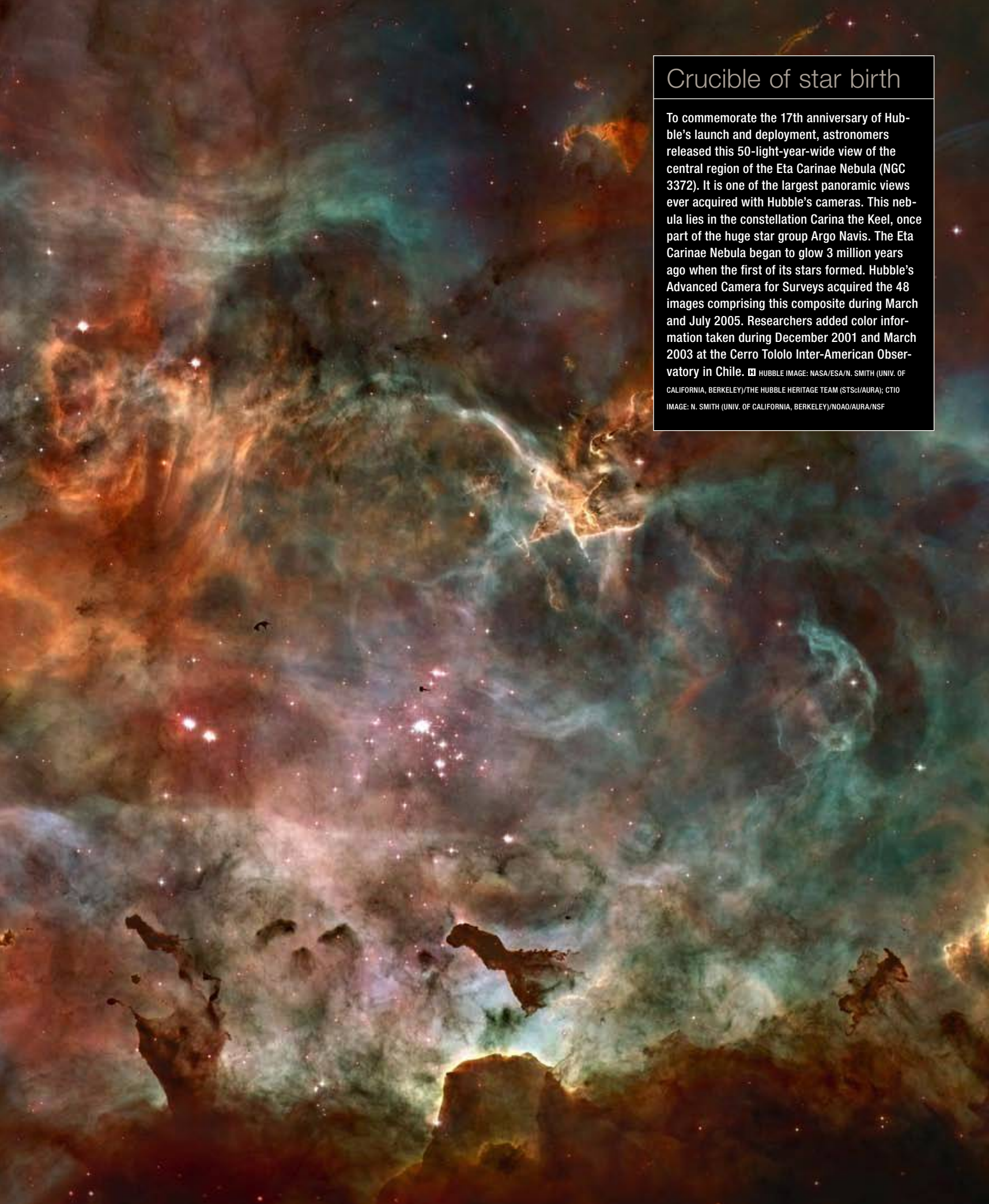
December 23, 1999
Shuttle astronauts replace Rate Sensing Units, which contain gyroscopes. Astronauts also install a new computer.

March 1, 2002
Space Shuttle Columbia (STS-109) launches, marking the fourth servicing mission (SM3B).

March 4–8, 2002
STS-109 astronauts install the Advanced Camera for Surveys (ACS), a new cryogenic cooler for the NICMOS, and new solar-array panels. NASA had launched the mission March 1 with Space Shuttle Columbia.

December 24, 2002
Hubble has traveled 2 billion miles since astronauts placed it in orbit.

October 31, 2006
NASA Administrator Michael Griffin announced a fifth servicing mission (SM4) to be launched in 2008.



Crucible of star birth

To commemorate the 17th anniversary of Hubble's launch and deployment, astronomers released this 50-light-year-wide view of the central region of the Eta Carinae Nebula (NGC 3372). It is one of the largest panoramic views ever acquired with Hubble's cameras. This nebula lies in the constellation Carina the Keel, once part of the huge star group Argo Navis. The Eta Carinae Nebula began to glow 3 million years ago when the first of its stars formed. Hubble's Advanced Camera for Surveys acquired the 48 images comprising this composite during March and July 2005. Researchers added color information taken during December 2001 and March 2003 at the Cerro Tololo Inter-American Observatory in Chile. H HUBBLE IMAGE: NASA/ESA/N. SMITH (UNIV. OF CALIFORNIA, BERKELEY)/THE HUBBLE HERITAGE TEAM (STScI/AURA); CTIO IMAGE: N. SMITH (UNIV. OF CALIFORNIA, BERKELEY)/NOAO/AURA/NSF

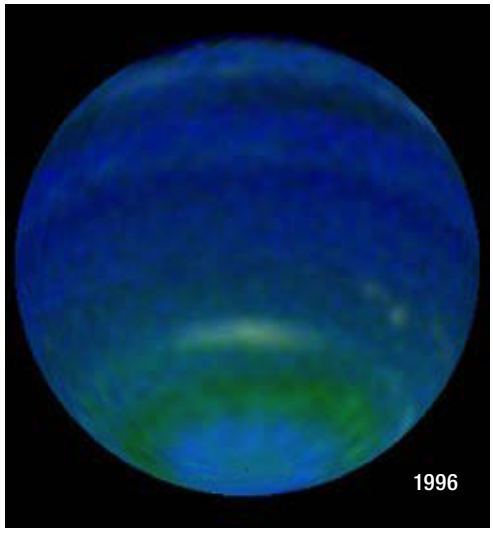
Neighborhood

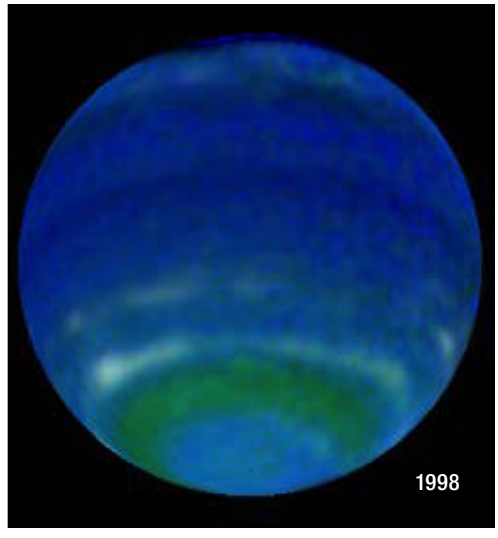
Hubble captured a comet collision, tracked planetary storms, and charted the outer solar system.

Planets differ from stars because planets don't give off their own light. Planets also are much less massive, so they orbit their stars.

The Sun, the planets, and other objects orbiting the Sun form the solar system. The word "solar" comes from the Latin word for Sun — *sol*. The name is appropriate, too, because the Sun comprises more than 99 percent of the solar system's material.

watch

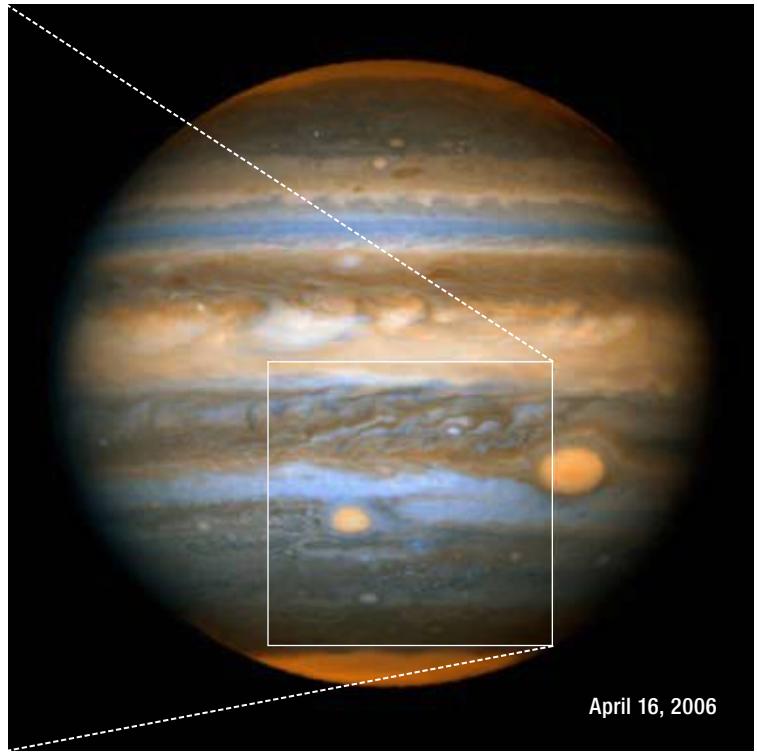




◄▲ **NEPTUNE** has brightened significantly since 1996, as shown in these comparative Hubble Wide Field and Planetary Camera 2 images. The rise is due to an increase of clouds observed in the planet's southern hemisphere, perhaps a seasonal change caused by a variation in solar heating.

Because Neptune's rotation axis is inclined 29° to its orbital plane, it is subject to seasonal solar heating during its long orbit of the Sun. Neptune's seasonal variation is 900 times smaller than Earth's because Neptune lies much farther from the Sun.

The rate at which Neptune's seasons change also is much slower because the planet takes 165 years to orbit the Sun. So, springtime in its southern hemisphere lasts several decades. NASA/L. SROMOVSKY AND P. FRY (UNIV. OF WISCONSIN)



SO MANY TARGETS, SO LITTLE TIME

A wide variety of objects populate our part of space. In addition to planets (major and dwarf), moons, asteroids, and comets speckle our solar system in mind-boggling profusion. Of the thousands of possible targets, Hubble can look at all but two: the Sun and Mercury. The Sun's great brilliancy would overwhelm Hubble's sensitive detectors in a microsecond, and Mercury lies too near the Sun for images to be taken safely.

Hubble's most frequently observed object, strangely enough, is Earth. At regular intervals, Hubble's charge-coupled device (CCD) cameras point toward Earth and take exposures. These images are for calibration only (and to test that the cameras still work) and show no detail.

Planetary roll call

Earth is the third planet from the Sun. Mercury and Venus (the inner, or inferior, planets) lie closer, and Mars, Jupiter, Saturn, Uranus, and Neptune (the outer, or superior, planets) lie farther away.

Except for Mars, the superior planets are larger than Earth and are mainly gas, with small rocky or metallic cores deep within. Because their compositions resemble Jupiter's, astronomers call Jupiter, Saturn, Uranus, and Neptune the jovian (or gas giant) planets. Mercury, Venus, Earth, and Mars all resemble Earth, so they're called the terrestrial (or rocky) planets.

Mercury and Venus travel in orbits smaller than Earth's, so they never appear far from the Sun from our vantage. At most, Mercury appears less than one-third of the distance from the horizon to the zenith (the overhead point), and Venus halfway up.

By far, Mars ranks as the most intriguing planet to astronomers because it's the most earthlike. Its day, 24 hours 37 minutes long, only slightly exceeds ours. Mars' tilt measures about 1.5° more than Earth's, which means Mars

◄ **VENUS** shows atmospheric features when imaged through ultraviolet (UV) filters. Hubble's WFPC-2 took this UV image January 24, 1995, when Venus was 70.6 million miles (113.6 million km) from Earth.

Venus is permanently shrouded by sulfuric-acid clouds, rather than the water-vapor clouds found on Earth. In UV wavelengths, cloud patterns become distinctive. In particular, a large, horizontal, Y-shaped cloud feature is visible near the equator. Bright clouds toward Venus' poles follow latitude lines.

The polar regions are bright, possibly because of a haze of small particles overlying the main clouds. The dark regions show the location of enhanced sulfur dioxide near the cloud tops.

L. ESPOSITO (UNIV. OF COLORADO)/NASA

▲ **RED SPOT JUNIOR,** as astronomers dubbed it, formed in Jupiter's atmosphere in 2006 after two smaller white spots merged. This storm measures roughly one-half the size of its bigger cousin, the Great Red Spot (GRS). The GRS' long axis stretches twice Earth's diameter, or about 15,000 miles (25,000 km).

Hubble's Advanced Camera for Surveys images, taken at near-infrared wavelengths, show the smaller spot as prominent as the GRS. This may mean Red Spot Jr. rises miles above Jupiter's main cloud deck like the GRS.

Astronomers still don't know why either spot appears red. One possibility is that the spots dredge up material from deeper in Jupiter's atmosphere. As this material rises, interaction with sunlight changes its color to red.

The left image combines red- and blue-filtered exposures. The right image shows Jupiter's entire disk and combines exposures through visible-light and near-infrared filters. This false-color image does not represent Jupiter's true appearance. Its purpose is to accentuate the two red spots and reddish high-altitude haze.

NASA/ESA/A. SIMON-MILLER (NASA/GSFC)/I. DE PATER (UNIV. OF CALIFORNIA, BERKELEY)

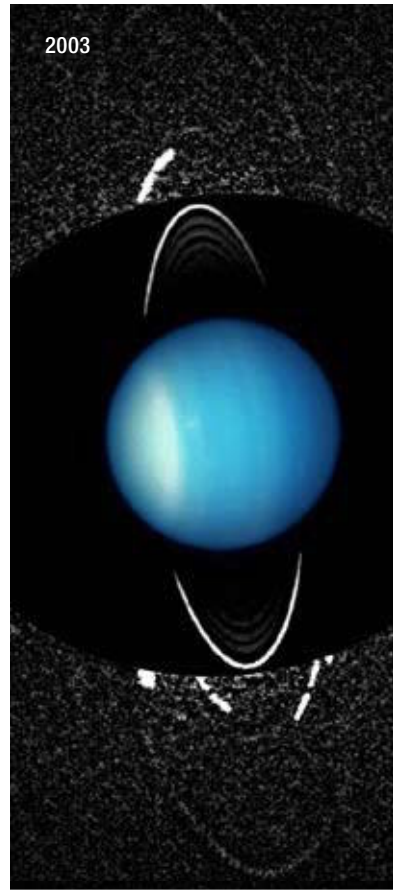
has similar seasons (albeit twice as long). Although it's cold on Mars (the planet's average temperature is –90° F [–68° C]), its temperature range falls closer to Earth's than any other planet's. Near Mars' equator in mid-summer, temperatures may exceed water's freezing point (32° F, or 0° C).

Also, we can see Mars' surface (which, in area, equals Earth's dry land) easily from Earth. And it's a surface that changes as Mars progresses through its seasons: Vast polar ice caps appear and disappear, new clouds form on a daily basis, large areas change in contrast, and dust storms — some planetary in scale — come and go.

Hubble has taken many images of Mars showing all of these features. In addition, it took probably the best-ever full-disk images of the Red Planet during Mars' opposition August 27, 2003. On that date, Mars approached its closest point to Earth in more than 50,000 years.

Superior planets all have orbits larger than Earth's because they lie farther from the Sun. When we observe these planets, we see only the tops of their atmospheres. Uranus shows little detail beyond a bluish-green coloration, even to Hubble's sensitive detectors, and Neptune is just slightly better. Jupiter and Saturn, however, are showpieces.

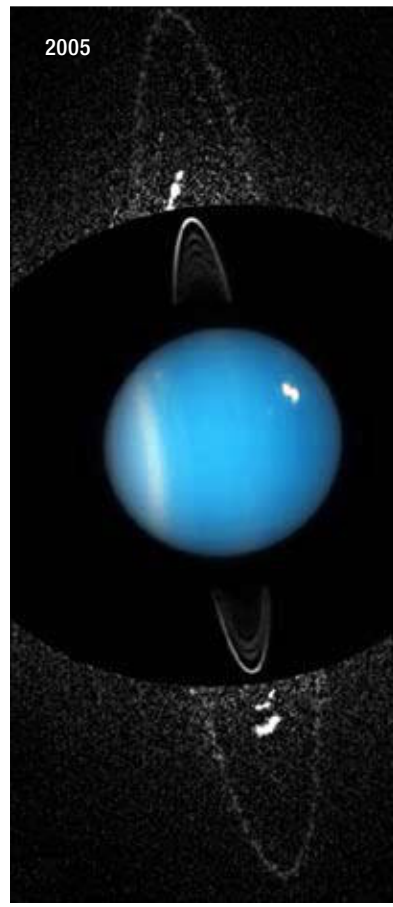
Both giant planets display ever-changing atmospheric belts and bands, with Saturn's being more subtle. What it lacks in surface detail, however,

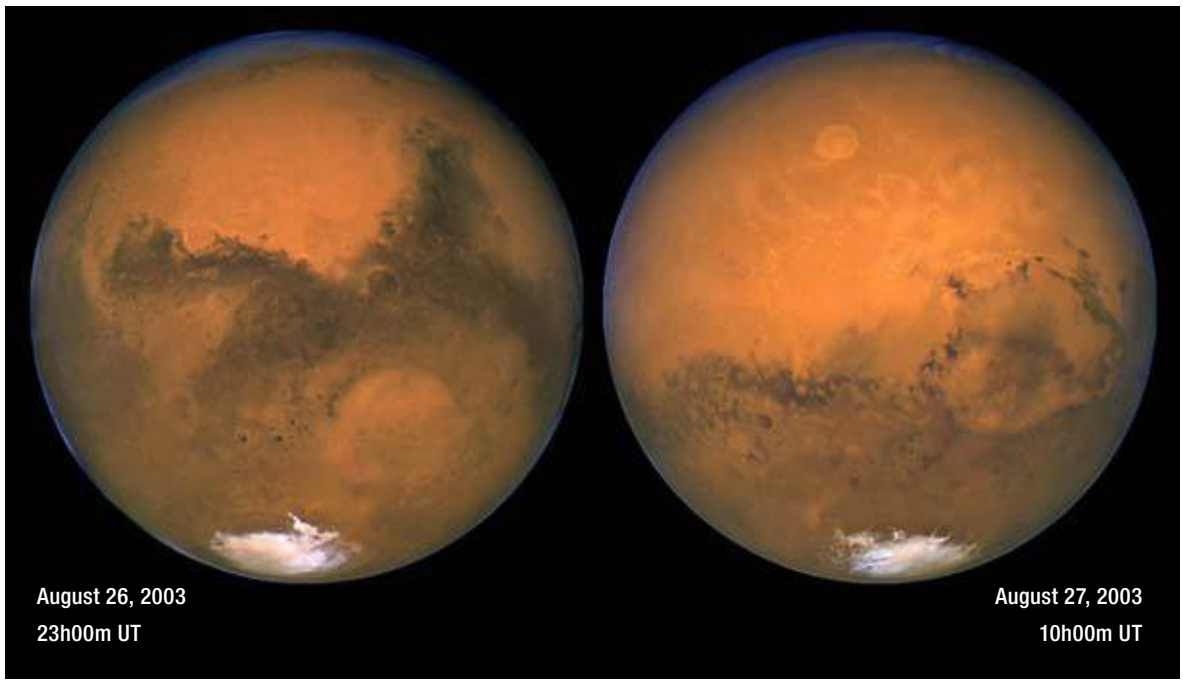


► **URANUS** has more rings than astronomers thought. These composite images reveal a pair of rings encircles the planet.

Hubble acquired the upper image in 2003. The new dusty rings appear faint and required long exposures to capture their image. The background speckle pattern is electronic noise in the image. The new, outermost ring measures twice the radius of the previously known ring system, seen near center. (The inner rings are much brighter, so no background noise appeared.)

In the bottom image, taken 2 years later, the rings appear more oblique because Uranus has moved along in its orbit. Cloud bands and storms appear more pronounced in the atmosphere. A bright storm (white spot) appears at northern latitudes in this image. NASA/ESA/M. SHOWALTER (SETI INSTITUTE)

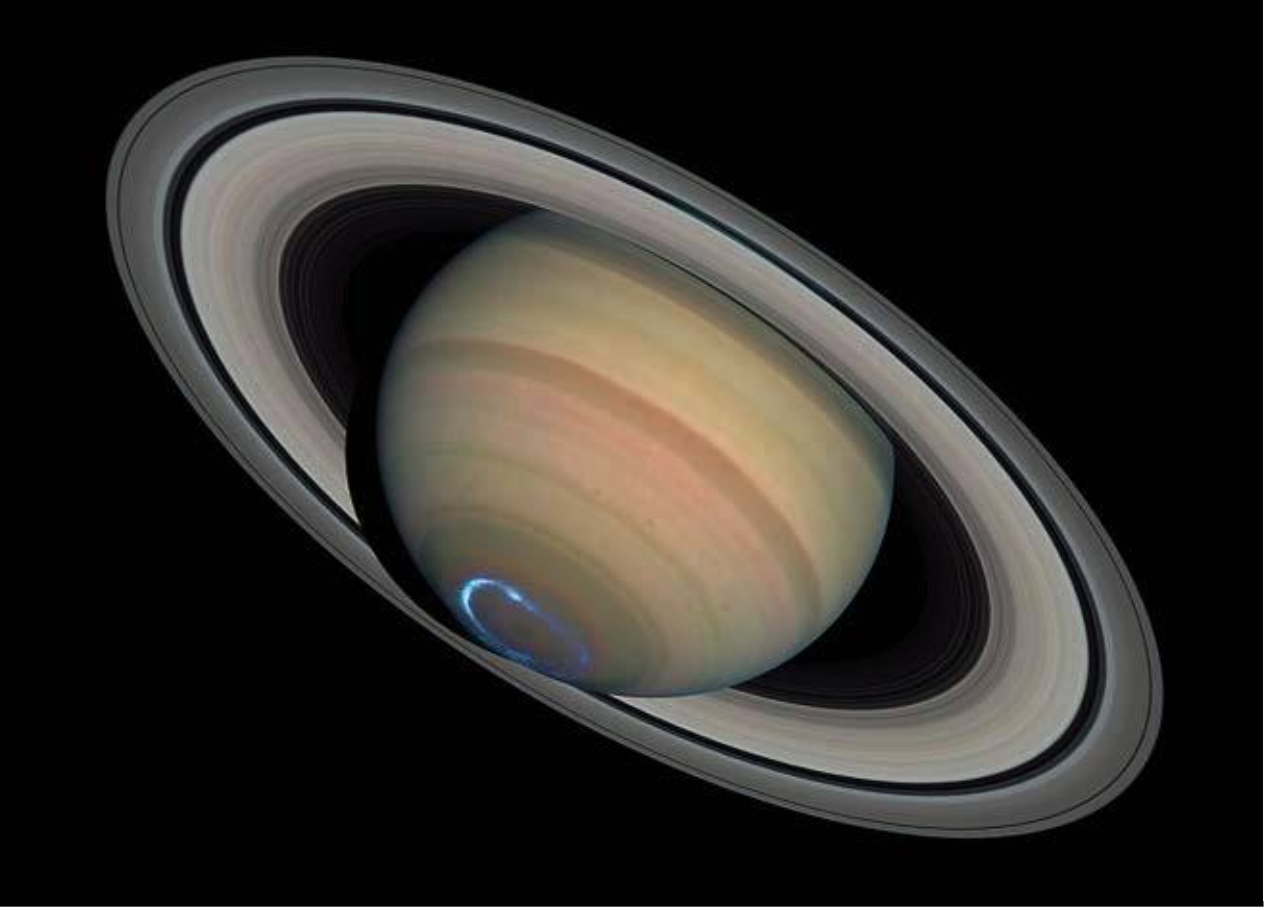


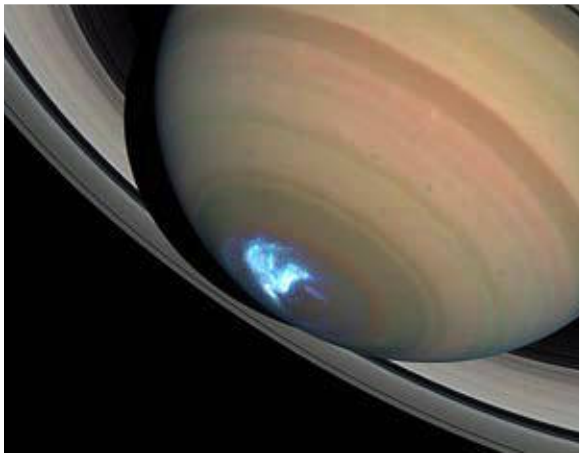


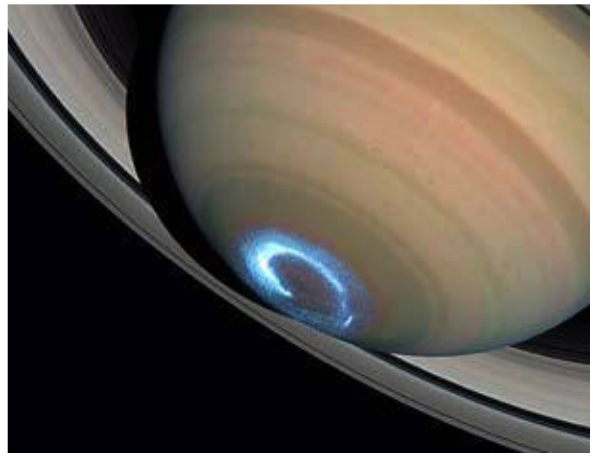
▲ **THESE TWO IMAGES** of Mars, taken 11 hours apart, reveal opposite sides of the Red Planet. Hubble's Wide Field and Planetary Camera 2 recorded the left image when Mars lay 34,648,840 miles (55,760,220 km) from Earth.

Hubble captured the right-hand image within minutes of Mars' closest approach to Earth for more than 50,000 years. At this moment, Mars and Earth were 34,647,420 miles (55,757,930 km) apart.

Both images show most of Mars' South Polar Ice Cap. At the time of these images, the Red Planet's southern hemisphere was in the middle of summer. Orange streaks over the ice are dust. NASA/J. BELL (CORNELL UNIV.)/M. WOLFF (SSI)







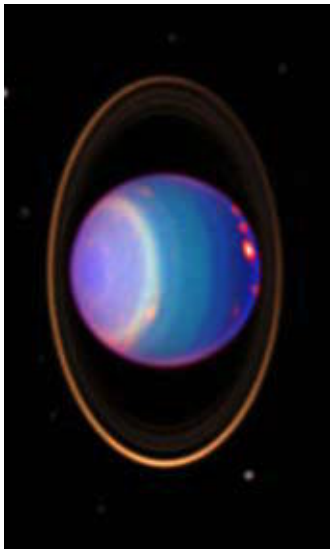
◄ **HUBBLE** revealed the dynamic nature of Saturn's aurorae. Viewing the planet's southern polar region for several days, Hubble snapped a series that shows Saturn's aurorae differ in character from day to day, moving around on some days and remaining stationary on others.

Compared with Earth, where auroral storms develop in about 10 minutes and may last for a few hours, Saturn's auroral displays always appear bright and may last for several days. Seen from space, an aurora appears as a ring of glowing gases near a planet's polar region.

Astronomers combined ultraviolet and visible-light images to make these pictures. The auroral display appears blue because of the glow of ultraviolet light. The aurora would appear red to an observer at Saturn because of the presence of glowing hydrogen in the atmosphere.

Hubble's Space Telescope Imaging Spectrograph took these images January 24, 26, and 28, 2004. The telescope's Advanced Camera for Surveys took visible-light images March 22, 2004.

NASA/ESA/J. CLARKE (BOSTON UNIV.)/Z. LEVAY (STScI)/ ERICH KARKOSCHKA (UNIV. OF ARIZONA)

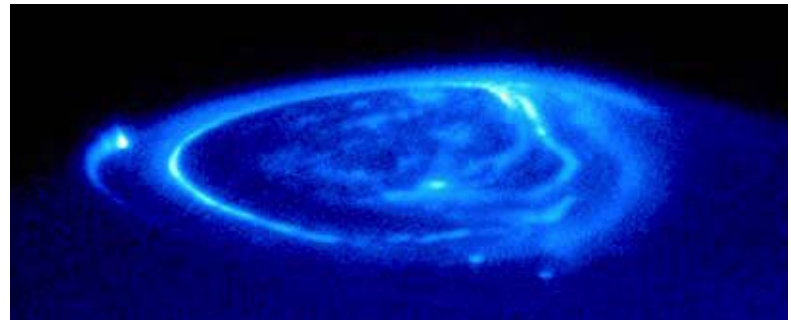


◄ **HUBBLE** revealed Uranus in this false-color image August 8, 1998. Hubble found about 20 clouds on Uranus — nearly as many as the previous total in the history of modern observations.

Orange-colored clouds near the prominent bright band circle the planet at more than 300 mph (500 km/h). One of the clouds on the right side is brighter than any other cloud ever seen on Uranus.

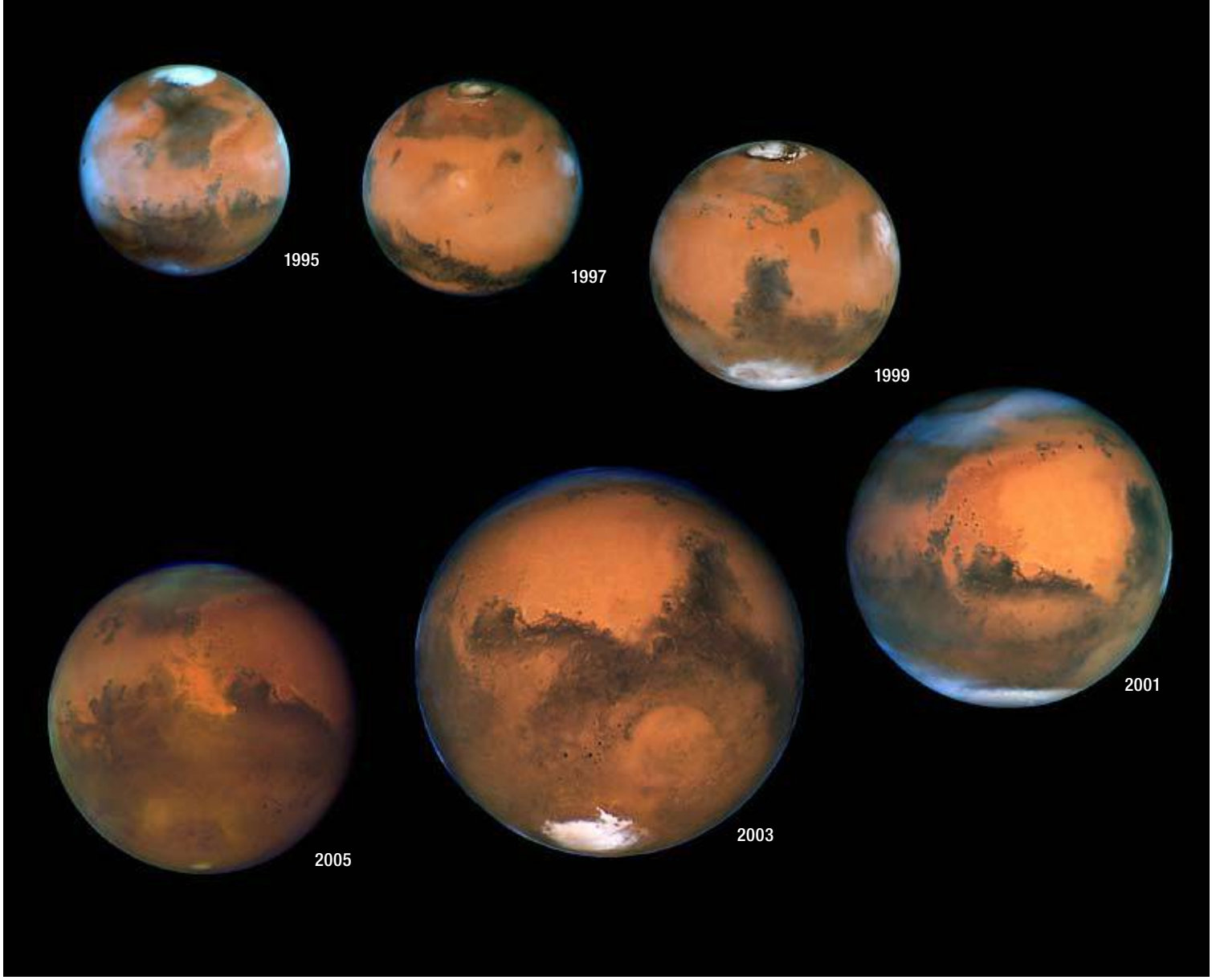
Image colors indicate altitude. Green and blue show where Uranus' sky is clear. In yellow and gray regions, sunlight reflects from a haze layer. Orange and red colors indicate high clouds.

ERICH KARKOSCHKA (UNIV. OF ARIZONA)/NASA



▲ **A JOVIAN AURORA** glows electric-blue in this Hubble image. Aurorae are curtains of light resulting from high-energy electrons racing along the planet's magnetic field into the upper atmosphere. The electrons excite atmospheric gases, causing them to glow.

The image shows the aurora's main oval, which is centered on the magnetic north pole, plus more diffuse emissions inside the polar cap. Hubble took this ultraviolet image with its Imaging Spectrograph November 26, 1998. In ultraviolet light, the aurora stands out clearly, but Jupiter's cloud structure is masked by haze. NASA/ESA/JOHN CLARKE (UNIV. OF MICHIGAN)



Saturn more than makes up for with its intricate, spectacular ring system. Hubble has examined Saturn's many rings in great detail, and astronomers have explained how the rings stay in place with the help of gravitational influences from the planet's satellites.

All four giant planets possess rings, but Saturn's stand out. Its ring system is large, and it contains small particles of ice and ice-covered rock. The rings around Jupiter, Uranus, and Neptune, on the other hand, contain dark particles and are not nearly as large as Saturn's.

Jupiter has been a favorite target for Hubble since NASA launched the spacecraft. In July 1994, Hubble imaged the gigantic "scars" left by the impacts of parts of Comet Shoemaker-Levy 9. Since then, Hubble has imaged jovian aurorae and followed the planet's changing cloud patterns and storm systems, including the largest, Jupiter's Great Red Spot.

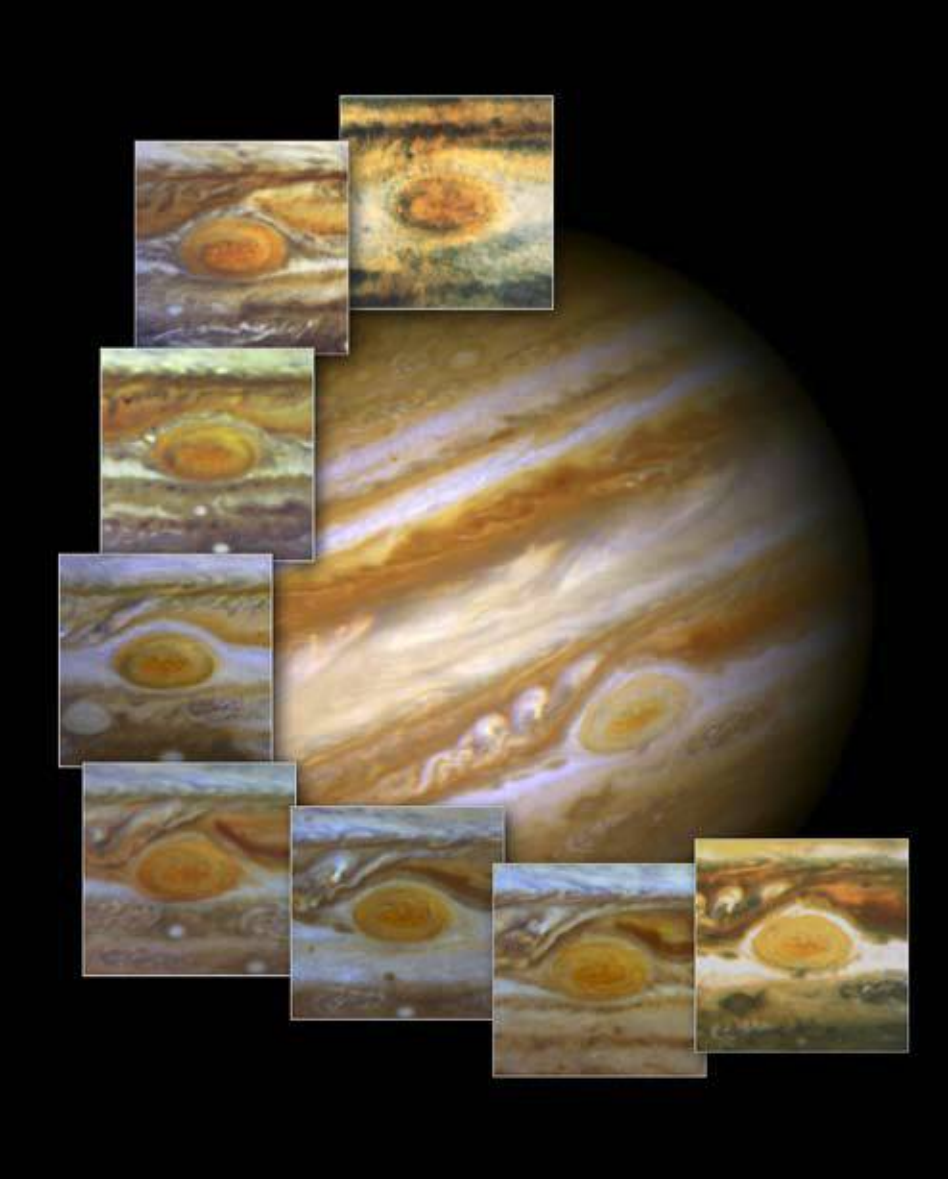
What about Pluto? From its discovery in 1930 until 2006, astronomers considered Pluto a major planet. In 2006, however, members of the International Astronomical Union (IAU) demoted Pluto to "dwarf planet" status. Nevertheless, Pluto remains a key solar system object. In March 1996, Hubble took the best-ever image of Pluto's surface, and in October 2005, it found two new small moons orbiting Pluto.

▲ **THE ORBITS** of Earth and Mars provide a planetary geometric line-up every 26 months, when Mars lies opposite the Sun in our night sky. Since Hubble's repair in 1993, Mars has been at "opposition" with the Sun six times.

Astronomers assembled this composite from each of the six Hubble opposition observations of the Red Planet. This mosaic shows relative variations in the apparent angular size of Mars through the years.

Mars lay closest in 2003, when it came within 34,570,000 miles (55,760,000 km) of Earth. The part of Mars tilted toward Earth also shifts over time, resulting in changing visibility of the martian polar caps.

Clouds and dust storms, as well as the ice caps' sizes, also can change Mars' appearance on time scales of days or weeks. Other features of Mars, however, such as some of the large dark markings, have remained unchanged for centuries and probably will look like this for the next few millennia. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



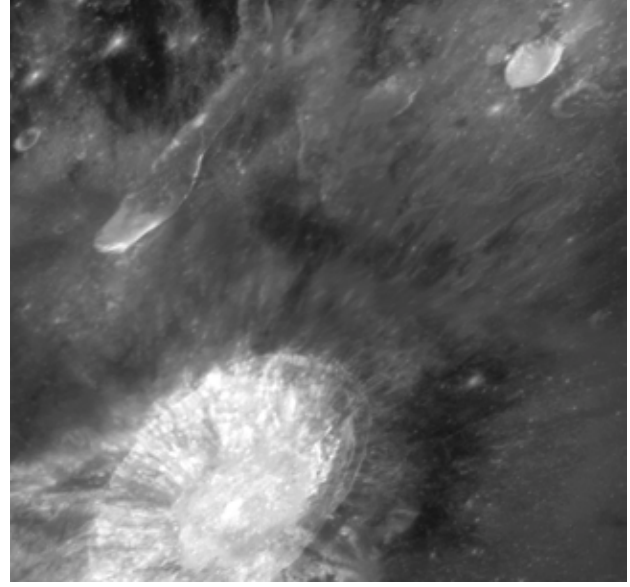
FOR CENTURIES, astronomers have watched a conspicuous red spot on Jupiter. The Great Red Spot (GRS) is a vast storm spinning like a cyclone.

Unlike a low-pressure hurricane on Earth, however, the Red Spot rotates in a counterclockwise direction in Jupiter's southern hemisphere, showing it is a high-pressure system. Winds inside the GRS reach speeds of 270 mph (435 km/h).

The Red Spot is the solar system's largest storm. With a length of 15,500 miles (25,000 km), it measures almost twice the size of Earth and one-sixth Jupiter's diameter.

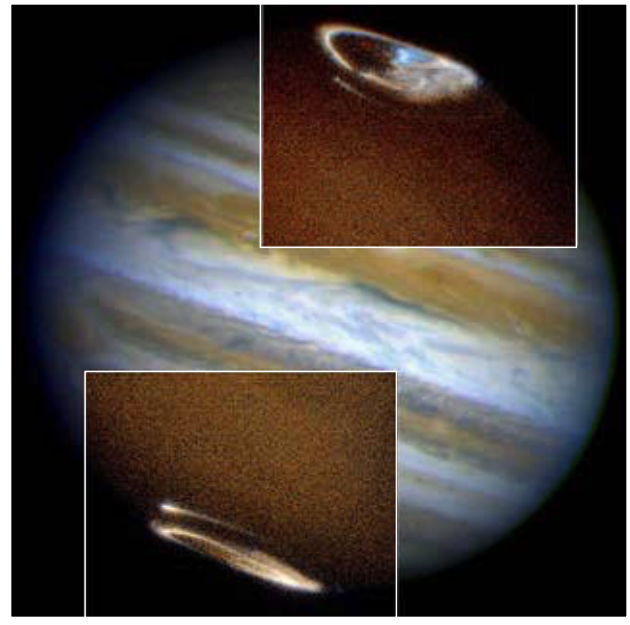
The GRS' long lifetime (some 400 years) may be due to the fact that Jupiter is primarily a gaseous planet. It lacks a solid surface, which would dissipate the storm's energy, much as happens when a hurricane makes landfall on Earth. However, the GRS changes shape, size, and color, sometimes dramatically.

Hubble captured such changes in the GRS with its Wide Field and Planetary Cameras 1 and 2. This mosaic presents a series of GRS images obtained between 1992 and 1999. THE HUBBLE HERITAGE TEAM (STScI/AURA/NASA)/AMY SIMON (CORNELL UNIV.)



HUBBLE rarely images the Moon, but when it does, the results are extraordinary. For this shot, Hubble's Advanced Camera for Surveys imaged Aristarchus crater and its surroundings August 21, 2005.

This image reveals fine-scale details of the crater's interior and exterior in ultraviolet and visible wavelengths at a scale of approximately 165 to 330 feet (50 to 100 meters) per pixel. NASA/ESA/J. GARVIN (GSFC)

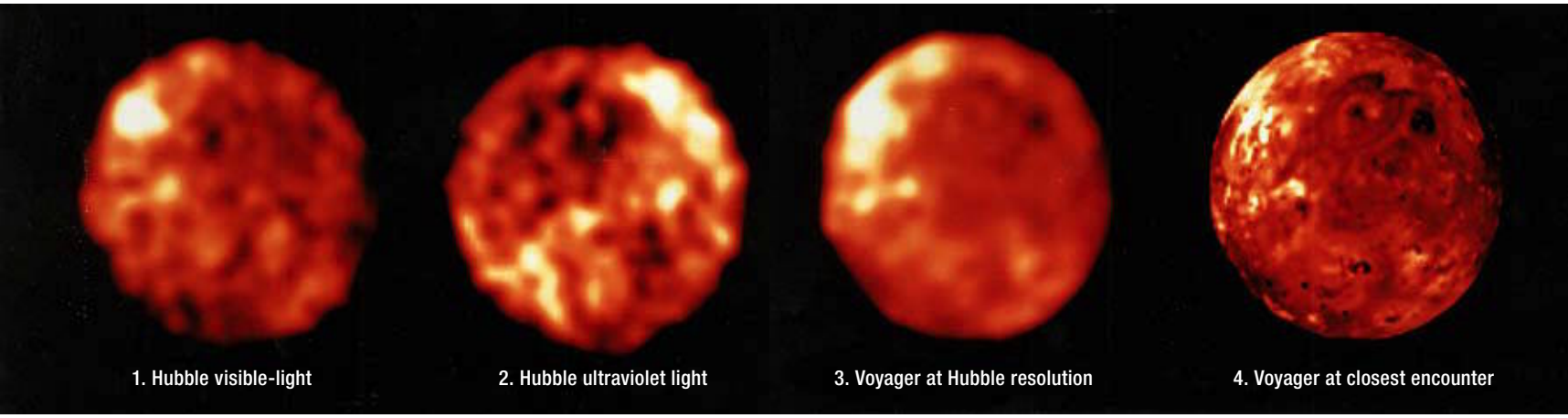


HUBBLE captured Jupiter's northern and southern aurorae in ultraviolet light with its Space Telescope Imaging Spectrograph. The curtain of auroral light extends several hundred miles above Jupiter's edge.

Scientists superimposed the images on a full-planet WFPC2 image. Jovian aurorae develop when charged particles trapped in the planet's magnetic field spiral toward the north and south magnetic poles. When these particles hit the upper atmosphere, they excite atoms and molecules there, causing them to glow.

The electrons that strike Earth's atmosphere come from the Sun, but Jupiter's aurorae have a different origin. Jupiter's magnetic field traps particles spewed out by Io's volcanoes.

Hubble took these images September 20, 1997. Astronomers created false colors by combining images taken in two different ultraviolet bands, one presented as blue and the other as red. The planet's reflected sunlight appears brown, while the auroral emissions appear white or as shades of blue or red. JOHN CLARKE (UNIV. OF MICHIGAN)/NASA



Shine on, Harvest Moons

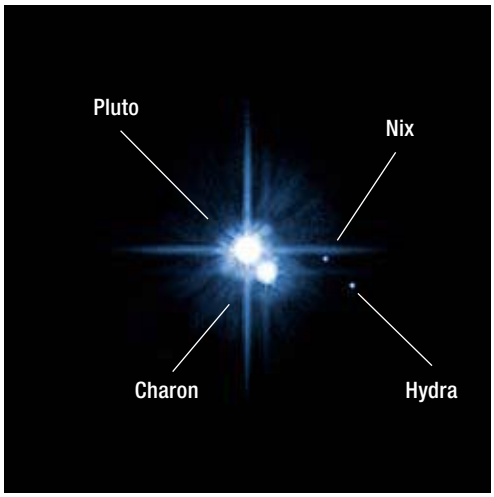
At last count, 166 moons orbited six planets. Mercury and Venus have no moons, and Pluto — with three — no longer has planetary status. Jupiter leads the pack with 63 satellites, and Earth brings up the rear with only one.

Many satellites, especially the small ones, formed as a result of collisions between larger bodies. Then the large planets (with their equally large gravity) captured the newly created moons. In at least one instance — Earth's Moon — a satellite formed because of a collision with the parent planet.

Early in solar system history, a Mars-sized object slammed into Earth. The collision ejected a vast amount of rocky material that formed a ring around Earth. Because of gravitational interactions among particles, the ring quickly coalesced into the Moon.

The first planetary satellites discovered (apart from the Moon) appeared to Italian astronomer Galileo Galilei (1564–1642) as he pointed his small telescope toward Jupiter in January 1610. Galileo saw four starlike points that changed their positions relative to the planet. He correctly guessed they were satellites orbiting Jupiter. Galileo's discovery was the first direct evidence of solar system bodies orbiting anything other than Earth. It helped confirm the Copernican theory, which says Earth is not at the center of the universe.

Astronomers, imaging with Hubble, have added to the satellite tally. The space telescope has found new moons orbiting major planets Saturn and Uranus and dwarf-planet Pluto.

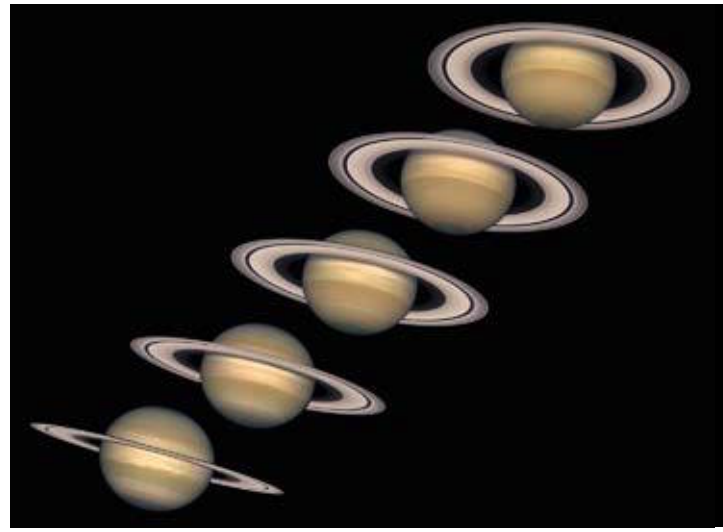


◄ **TWO NEW MOONS** orbit Pluto in this eagerly awaited Hubble follow-up observation February 15, 2006. Hubble imaged the moons in May 2005, but the science team probed even deeper into the Pluto system in February 2006 to look for additional satellites and to characterize the satellites' orbits. The two new moons, named Nix and Hydra, join Charon, which American astronomer James Christy discovered in 1978. Each moon glows 5,000 times fainter than Pluto. NASA/ESA/H. WEAVER (JHU/APL)/A. STERN (SOUTHWEST RESEARCH INSTITUTE)/HST PLUTO COMPANION SEARCH TEAM

▲ **JUPITER'S MOON IO** was 414 million miles (670 million km) from Earth March 15, 1992, when Hubble took the visible-light image (1) of its geologically active trailing hemisphere. Hubble resolved features as small as 150 miles (242 km) across.

An ultraviolet-light (UV) picture (2) of the same hemisphere shows Io's surface. Regions bright in visible light are dark in UV, probably because a sulfur-dioxide frost (a strong absorber of UV) covers large areas of Io.

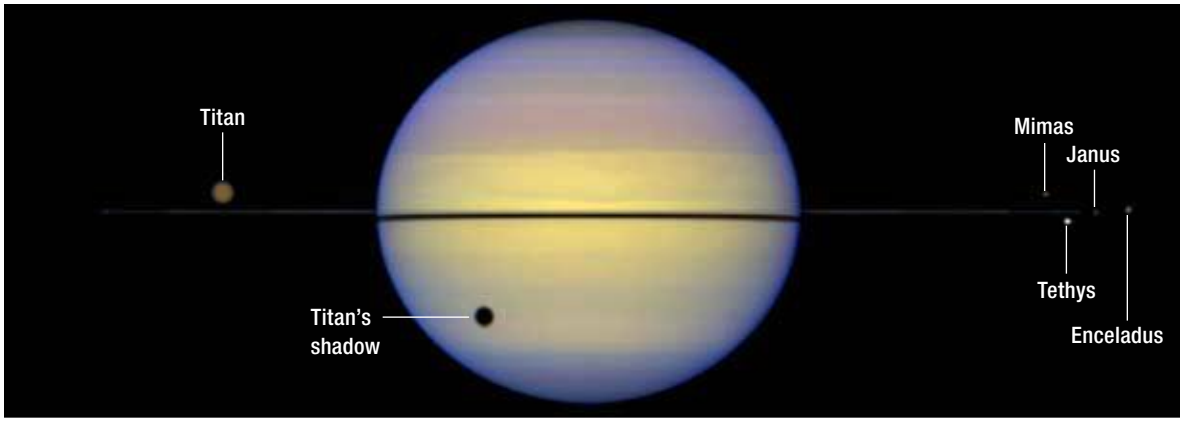
Voyager images, taken in 1979 by the Voyager 1 and Voyager 2 spacecraft, provide a comparison in image resolution. FRANCESCO PARESCE (ESAI (STScI)/PAOLA SARTORETTI (UNIV. OF PADOVA)

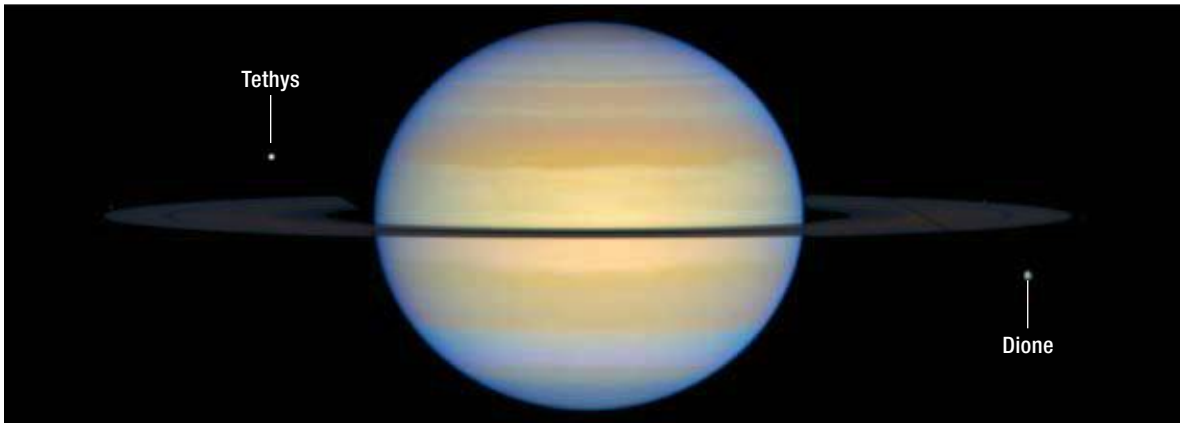


▲ **SATURN** puts on a show as the planet and its magnificent ring system nod majestically during its 29-year journey around the Sun. These Hubble Space Telescope images, captured from 1996 to 2000, show Saturn's rings open up from just past edge-on to nearly fully open as the ringed planet moves from autumn toward winter in its Northern Hemisphere.

Astronomers are studying this set of images to investigate variations in the ring system's color and brightness. Saturn's rings measure only about 30 feet (10 meters) thick. The rings are made of dusty water ice in the form of boulder-sized and smaller chunks that graze one another as they orbit Saturn.

Saturn's gravitational field constantly disrupts the particles. This force keeps them spread out and prevents them from combining to form a moon. NASA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

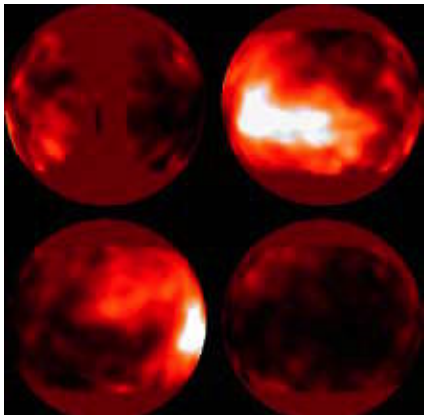




◄ **A RING-PLANE** crossing happens when Earth passes through the plane of Saturn's rings. The top image shows Saturn with its rings barely visible. Normally, Saturn's rings appear tilted.

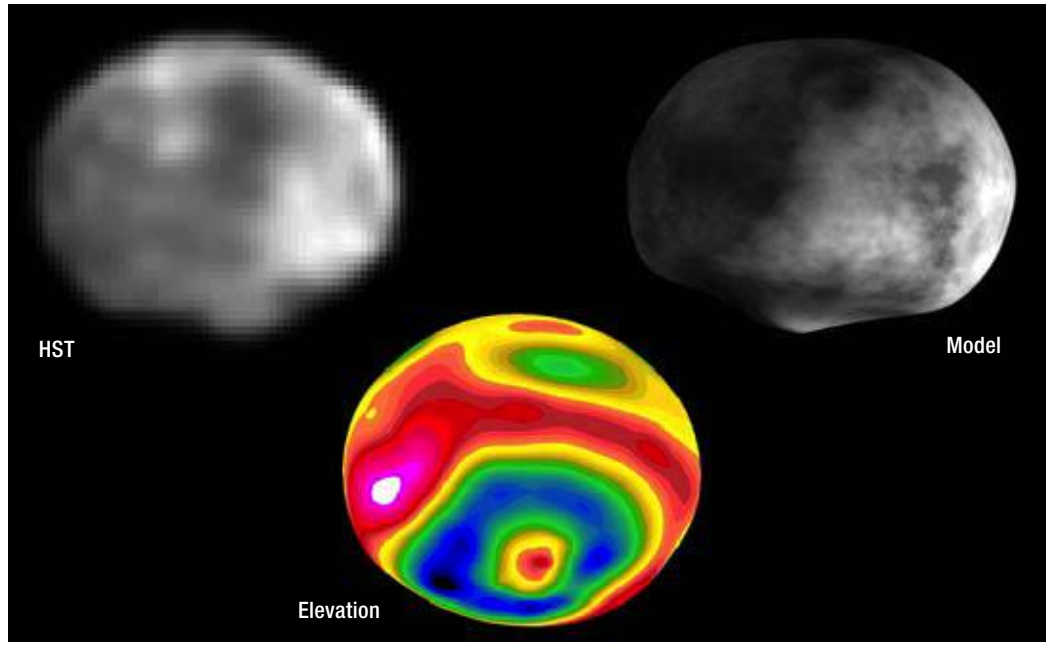
In this view, Saturn's largest moon, Titan, casts a shadow on Saturn. Titan looks brown because of its atmospheric haze. The other moons appear white because of their bright, icy surfaces. Four moons — from left to right, Mimas, Tethys, Janus, and Enceladus — cluster at the edge of Saturn's rings on the right.

The bottom image shows Saturn's rings slightly tilted. The moon Dione, on the lower right, is casting a long, thin shadow across the whole ring system because of the setting Sun's position. The moon to Saturn's upper left is Tethys. Astronomers assembled the images from separate exposures taken August 6 (top) and November 17, 1995, with WFPC2. ERICH KARKOSCHKA (UNIV. OF ARIZONA LUNAR AND PLANETARY LAB)/NASA



▲ **THE FOUR CORNERS** of Saturn's largest moon Titan reveal great detail through Hubble's eyes. These four global projections lie 90° apart in longitude.

The upper-left image shows the hemisphere facing Saturn. At upper right is the leading hemisphere (the brightest region). The lower-left image shows the hemisphere that never faces Saturn. At lower right is the trailing hemisphere. The imaging team's data strongly support a synchronous rotation for Titan, but this idea needs further study and proof. UNIV. OF ARIZONA LUNAR AND PLANETARY LAB/STScI



▲ **ASTEROID 4 VESTA** is the brightest asteroid visible from Earth. At left, Hubble imaged Vesta in May 1996, when the asteroid was 110 million miles (177 million km) from Earth. The asteroid's asymmetry and "nub" at the south pole suggest it suffered a large impact event.

At center, a color-coded elevation map shows a giant 285-mile-diameter (460 km) impact basin and "bull's-eye" central peak. The map combines 78 WFPC2 pictures. Scientists estimated surface topography, noting irregularities along the limb and at the terminator (day/night boundary), where the low Sun angle enhances shadows.

At right, astronomers constructed a three-dimensional computer model of Vesta synthesized from Hubble topographic data. The crater's 8-mile-high (13 km) central peak lies near the asteroid's pole. BEN ZELLNER (GEORGIA SOUTHERN UNIV.)/PETER THOMAS (CORNELL UNIV.)/NASA

◄ A MOON CROSSING Uranus had never before been seen until Hubble's Advanced Camera for Surveys took this image July 26, 2006. Astronomers call such passages transits.

Uranus orbits the Sun once every 84 years. Because Uranus' axis tilts 98° to Earth's orbital plane, the planet's poles and equator alternately face the Sun (and Earth) during seasons that last 21 years. Uranus' moons orbit the planet above its equator, so their paths align edge-on to the Sun only every 42 years.

The last time astronomers could have seen a satellite transit Uranus was in 1965. Back then, however, no telescope had the resolution required to see such an event. NASA/ESA/L. SROMOVSKY (UNIV. OF WISCONSIN)/ H. HAMMEL (SPACE SCIENCE INSTITUTE)/K. RAGES (SETI)

Minor planet tally

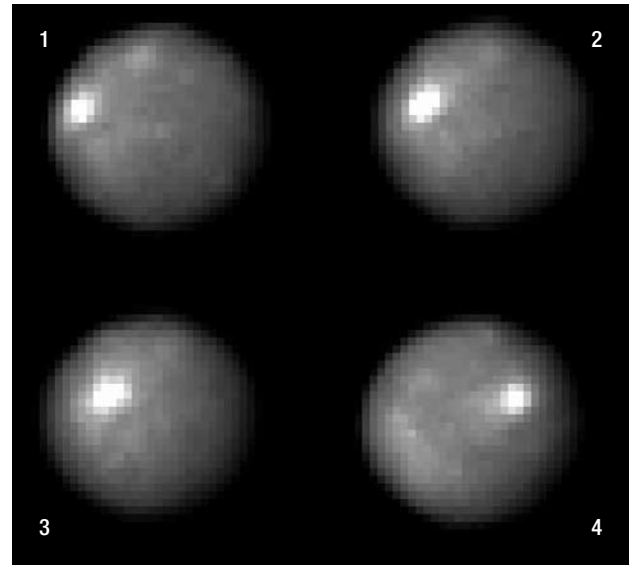
Between the orbits of Mars and Jupiter lies the asteroid belt. Since the first asteroid's discovery, in 1801, astronomers have called these objects minor planets. With the IAU's 2006 planetary reclassification, however, scientists now recognize only two planet classes — major and dwarf. All bodies that are not planets or satellites now fall under the category "small solar system bodies."

Careful counts by planetary astronomers suggest a total of about 300,000 asteroids with diameters between half a mile and 2 miles (1 to 3 km) exist. Only 16 asteroids measure more than 150 miles (240 km) across. These objects didn't form as a result of a planetary collision but were primordial bits left over after the large bodies formed. In fact, if we could somehow combine all the asteroids into one body, it would measure about 900 miles (1,500 km) across — less than half the Moon's diameter.

The largest asteroid, Ceres — now classified as a dwarf planet, the only one in the asteroid belt — measures 590 miles (950 km) across. The brightest asteroid, Vesta, is easy for most observers to spot through binoculars from a dark site. At times, its brightness increases to naked-eye visibility.

Some asteroids lie closer to the Sun than the asteroid belt. These near-Earth objects (NEOs) approach close to Earth, and, in the future, may threaten our existence. Planetary scientists, therefore, track them carefully.

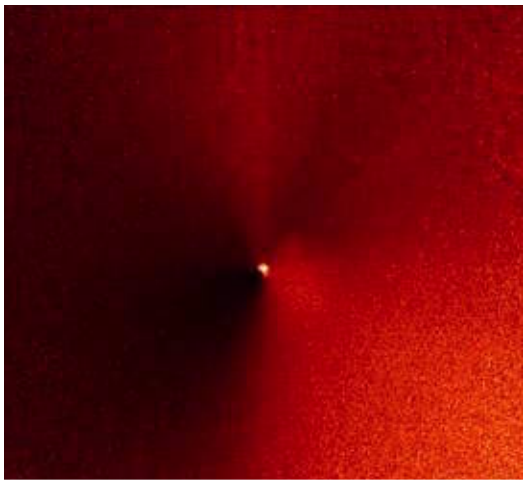
Astronomers have stumbled onto an unusual asteroid hunting ground: the thousands of Hubble images stored in the orbiting observatory's archive. The hunt has yielded a sizeable catch of small asteroids — about 100. More surely remain to be found.

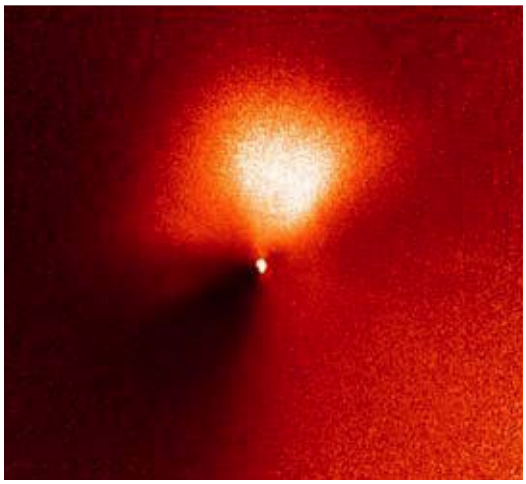


▲ THE ASTEROID 1 Ceres rotated under Hubble's gaze between December 2003 and January 2004. It recorded these four images over a 2-hour-and-20-minute span, about one-quarter of Ceres' 9-hour day.

Hubble recorded 267 images of Ceres, the largest asteroid, as Ceres rotated once. Astronomers confirmed Ceres is nearly round. Its shape suggests its interior is layered, like that of Earth. Ceres may have a rocky inner core, an icy mantle, and a thin, dusty outer crust (inferred from its density and rotation rate).

The bright spot in each image is a mystery. It is brighter than its surroundings, but it reflects only a small portion of the sunlight falling on it. NASA/ESA/J. PARKER (SOUTHWEST RESEARCH INSTITUTE)/P. THOMAS (CORNELL UNIVERSITY)/L. McFADDEN (UNIV. OF MARYLAND)





Comets

Once thought to be evil omens sent by the gods to warn humanity of impending doom, bright comets have an observation record stretching back thousands of years. Today, they tell astronomers a complicated story.

Comets represent pristine chunks of the early solar system. Each comet is a "dirty snowball" of gas and some trapped dust that formed more than 4.6 billion years ago in the outskirts of the solar system. Periodically, they journey into the inner solar system as they loop around the Sun. By studying what lies beneath the surfaces of comets, scientists can determine the original composition of the cloud out of which the Sun and planets formed.

During the 1990s — Hubble's first decade — humanity witnessed a pair of brilliant nighttime comets (Hyakutake in 1996 and Hale-Bopp in 1997) and another that, although invisible to the eye, left a mark not soon forgotten.

In July 1994, Comet Shoemaker-Levy 9, which previously had broken apart into 21 pieces, struck Jupiter. Although the impacts occurred out of sight behind Jupiter for earthbound observers, they left several dark "scars" in Jupiter's atmosphere. This event provided planetary astronomers with lots of questions and presented Hubble with some great imaging targets.

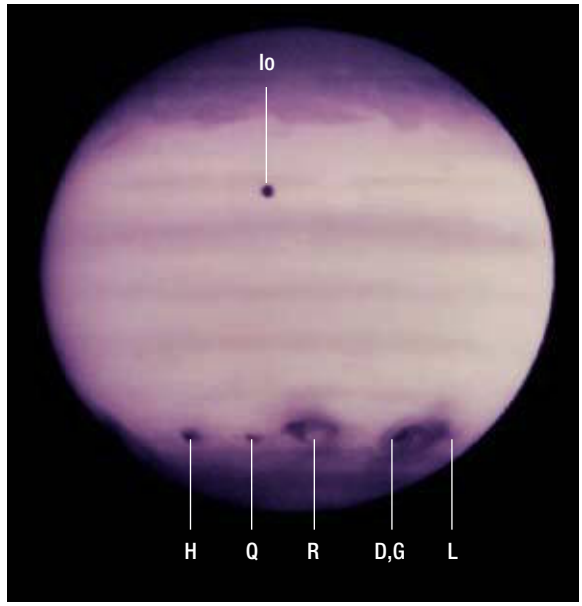
In this decade, Hubble studied Comet 67P/Churyumov-Gerasimenko to prepare for ESA's Rosetta mission, which is designed to land a space probe on the comet in 2014. Also, on July 4, 2005, Hubble imaged the collision between an 820-pound (373 kg) projectile released by the Deep Impact spacecraft and Comet 9P/Tempel 1. Nearly a year later, in April 2006, Hubble captured the disintegration of Comet 73P/Schwassmann-Wachmann. Hubble images uncovered many more fragments than ground-based observers reported. H

▲ **COMET** 9P/Tempel 1 had an outburst prior to its rendezvous with NASA's Deep Impact spacecraft in July 2005. Hubble captured these dramatic images of a new jet of dust streaming from the comet.

The images, taken June 14, show Tempel 1's icy nucleus is dynamic and volatile. Astronomers hoped this eruption would be a preview of the fireworks July 4, when a probe from the Deep Impact spacecraft slammed into the comet, and, indeed, it was.

The two images, spaced 7 hours apart, show Tempel 1 and its new jet. At top is a pre-outburst view of the comet. The bright dot is the comet's nucleus.

The bottom image reveals the jet (the bright fan-shaped area) extending about 1,400 miles (2,200 kilometers). ASA/ESA/P. FELDMAN (JOHNS HOPKINS UNIV.)/ H. WEAVER (JOHNS HOPKINS UNIV. APPLIED PHYSICS LAB)



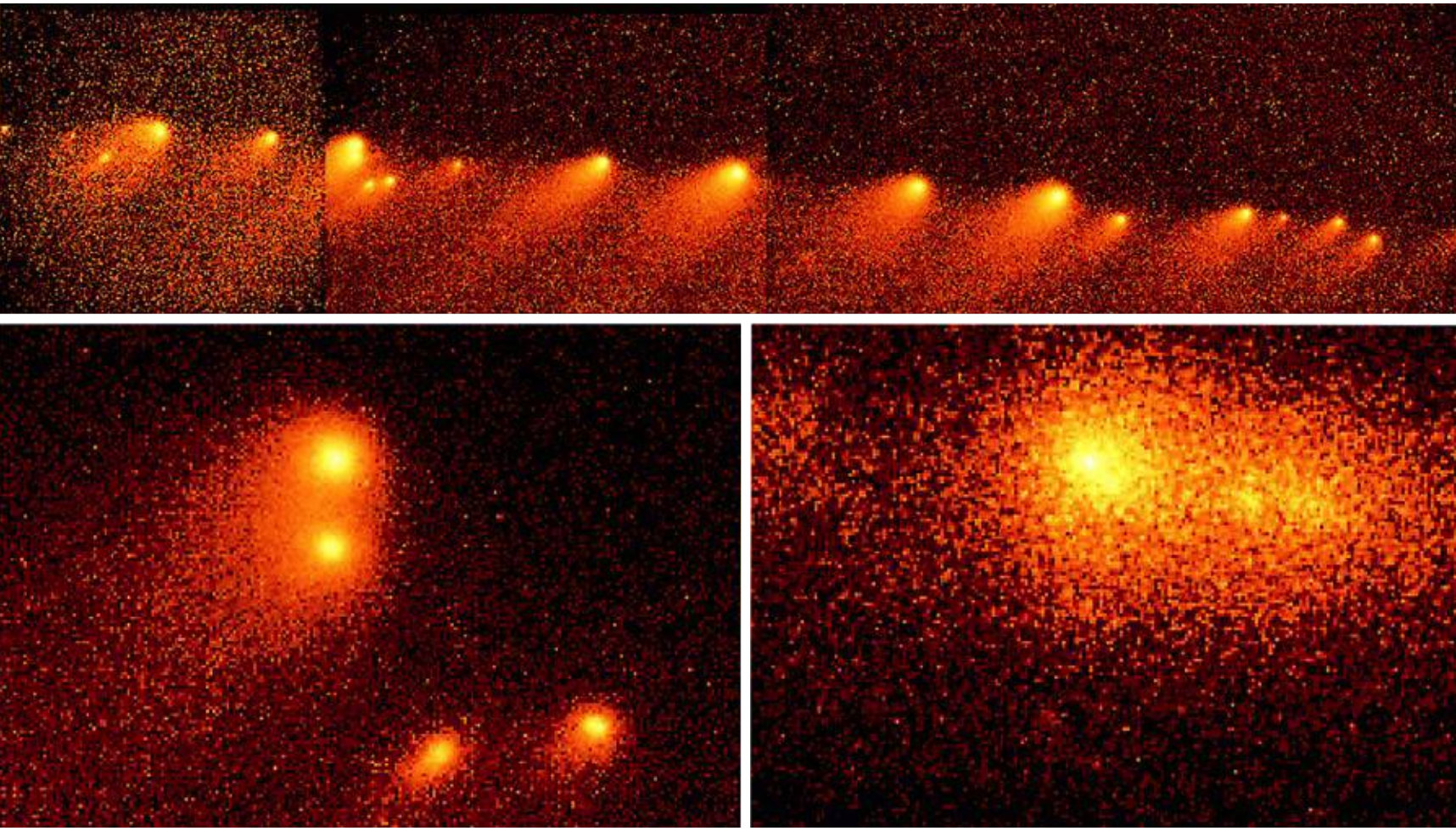
◄ **THIS ULTRAVIOLET** image, taken with the Wide Field and Planetary Camera, shows Jupiter's atmosphere after impacts by Comet Shoemaker-Levy 9. Fragment R's "scar" was the most recent. It lies below center (third dark spot from the right).

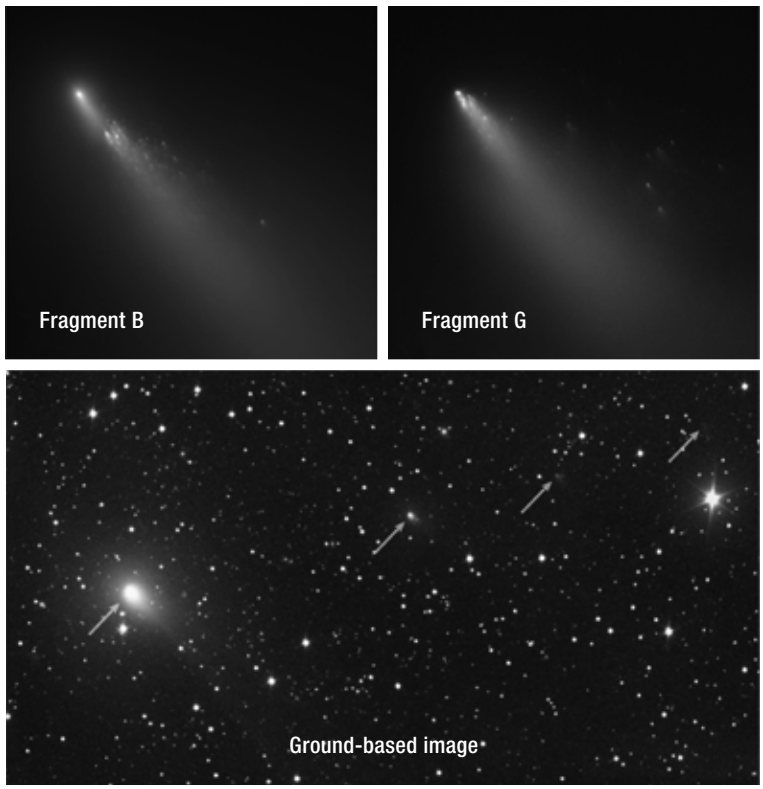
A large dark patch from the impact of fragment H rises on the morning (left) side. Proceeding to the right, other dark spots were caused by impacts of fragments Q, R, D and G (now one large spot), and L, with L covering the largest area.

The spots appear dark when imaged through ultraviolet filters because the comet's fragments deposited a large quantity of sunlight-absorbing dust high in Jupiter's stratosphere. Scientists watched the evolution of these features to track upper-level jovian winds.

Jupiter's moon Io is the dark spot just above the planet's center. Hubble took this photo July 21, 1994, about 2½ hours after R's impact.

HST COMET SCIENCE TEAM





◄ **COMET** 73P/Schwassmann-Wachmann 3 fell apart right before our eyes. Hubble images disclosed many more fragments than seen by ground-based observers. These observations provide an unprecedented opportunity to study the demise of a comet nucleus.

When Hubble took this image, the comet was a chain of three dozen separate fragments stretching across several degrees on the sky. Hubble caught two of the fragments, B and G, (top frames) shortly after large outbursts in activity.

The images reveal a hierarchical destruction process took place, in which fragments continued to break into smaller chunks. Whether any of the many fragments survived the trip around the Sun remains to be seen. HUBBLE IMAGES: NASA/ESA/H. WEAVER (JHU/APL)/M. MUTCHLER AND Z. LEVAY (STScI); GROUND-BASED IMAGE: GERALD RHEMANN AND MICHAEL JÄGER

▲ **TWENTY-ONE** fragments of Comet Shoemaker-Levy 9 struck Jupiter in July 1994. Hubble imaged the cometary chunks before they plunged into the giant planet's atmosphere.

Jupiter's gravity tore the comet into pieces as it passed by in summer 1992. The 11 largest comet fragments measured 1½ to 2½ miles (2 to 4 km) in diameter. Hubble first observed the comet July 1, 1993.

The top image is a mosaic showing 20 fragments. Hubble took the lower-right image with the Planetary Camera before the first servicing mission in December 1993. The image shows the region of the brightest comet fragment. Four fragments are barely discernible in this view.

Hubble acquired the lower-left image after the servicing mission, and the comet fragments appear much more clearly. H. A. WEAVER (JHU/APL) AND T. E. SMITH (STScI)/NASA

Raising the bar

Barred spiral galaxy NGC 1300 lies 70 million light-years away in the constellation Eridanus the River. Unlike regular spiral galaxies, whose long, sinuous arms start at their centers, galaxies like NGC 1300 possess a thick bar composed of billions of stars. Their spiral arms begin at either end of the bar. In 2006, data from the Spitzer Space Telescope confirmed the Milky Way also is a barred spiral galaxy. This composite, created from images taken in September 2004, is one of the largest Hubble images ever made of a complete galaxy. Due to the galaxy's large size, two adjacent pointings of the telescope were necessary to cover the extent of the spiral arms. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

Great balls of

Some stars are quiet, some catastrophically violent, and some harbor hidden planets.

fire

▲ **INFANT STARS** glow in the Small Magellanic Cloud (SMC), which is visible to the naked eye in the southern constellation Tucana the Toucan and located 210,000 light-years away. Hubble's Advanced Camera for Surveys revealed a population of some 2,500 young stars embedded in the nebula NGC 346 that are still forming from gravitationally collapsing gas clouds.

The stars — only 5 million years old — have not yet begun to fuse the hydrogen in their cores. The smallest of these infant stars contains only half the Sun's mass. Although star birth is common within the disk of our galaxy, the SMC is more primeval because it has only a small percentage of the elements heavier than hydrogen and helium, which successive generations of stars forged through nuclear fusion. The SMC offers a unique nearby laboratory for understanding how stars arose in the early universe. NASA/ESA/A. NOTA (STScI/ESA)

FUSION COOKING

Stars like the Sun shine because nuclear reactions in their cores transform the centers (nuclei) of hydrogen atoms into helium nuclei. Such a reaction is called fusion because, at such high temperatures (typically tens of millions of degrees), the fast-moving particles join, or fuse, when they strike one another in just the right way. Eventually, this process forms a heavier element, helium. Because a hydrogen nucleus has one proton, this particular fusion process is called the proton-proton cycle.

Stars more massive than the Sun, or Sun-like stars in the late stages of their lives, have higher core temperatures, up to hundreds of millions of degrees. At such high temperatures, elements heavier than hydrogen fuse. Helium, for example, fuses into carbon. This process ends with iron.

During nuclear fusion, a tiny bit of energy escapes each time a helium nucleus forms. Because a huge number of these transformations occurs each second, Sun-like stars emit lots of energy. Astronomers estimate that each second the Sun shines, more than half a billion tons of hydrogen becomes helium within its core. The Sun is so massive, however, this process has been going on for 4.5 billion years. It will continue for another 5 billion years.

▲ **SWEEPS,** the Sagittarius Window Eclipsing Extrasolar Planet Search, examines lots of stars. This image shows approximately 150,000 stars, down to 30th magnitude.

Half of these stars are bright enough for Hubble to monitor for periodic dips in brightness caused by a planet passing in front of the star. Hubble took 520 pictures of this field from February 22–29, 2004.

Astronomers identified nine stars orbited by planets with periods of a few days. These are "candidate" exoplanets because most are too faint for follow-up observations. Such observations would provide a precise measure of each planet's mass.

Astronomers even measured one star spectroscopically, showing its back-and-forth wobble due to the planet's pull. The planet's mass is less than 3.8 times that of Jupiter. NASA/ESA/K. SAHU (STScI)/THE SWEEPS SCIENCE TEAM

Step out on a clear, moonless night, and overhead you'll see several thousand bright, shimmering points of light. The stars that cover the sky seem uncountable, but a person with average vision at a dark, cloudless site would tally only about 2,500 stars. These stars are visible as individual points of light for two reasons: They are bright or they lie close to Earth. In some cases, both are true.

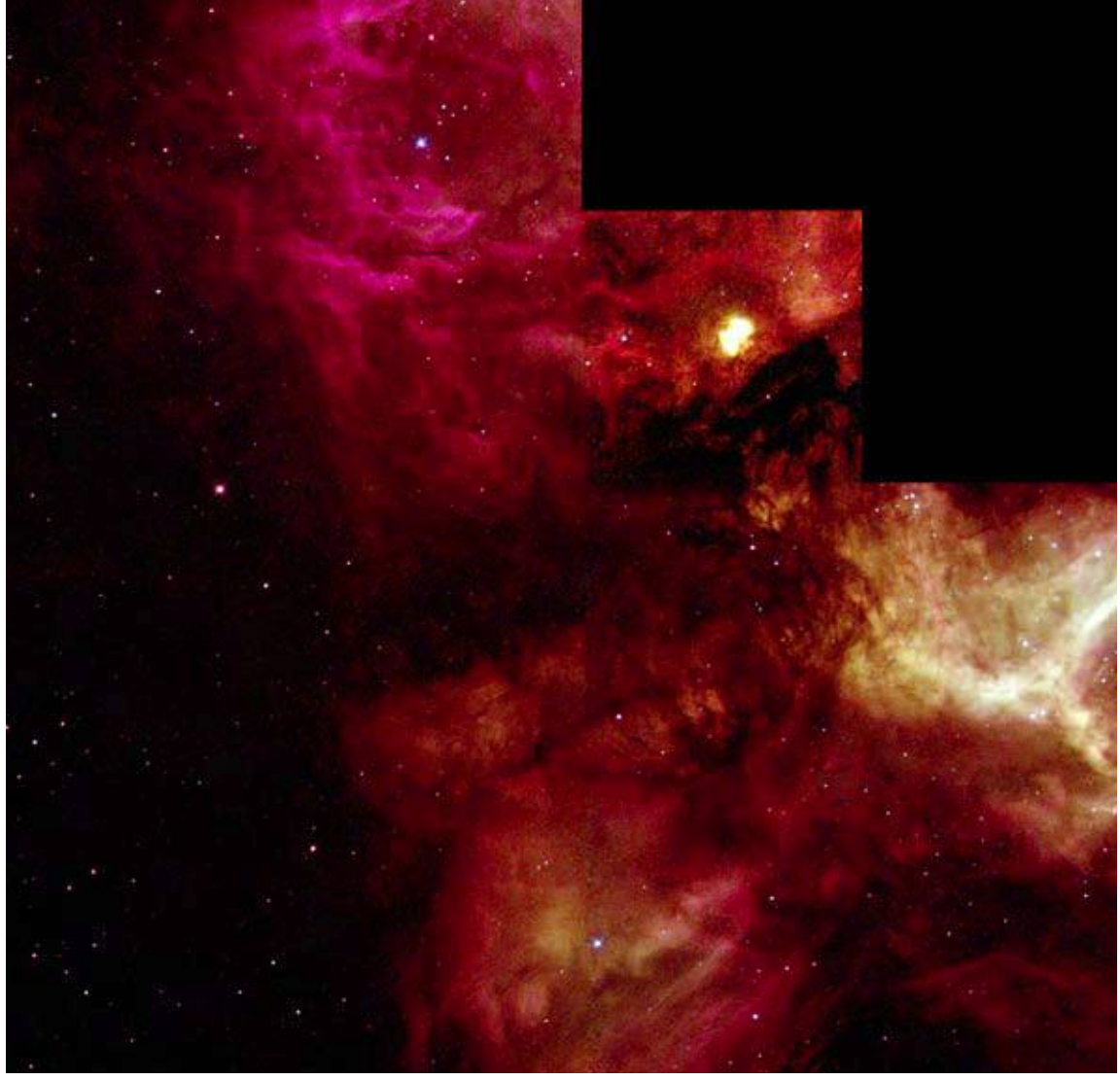
All stars fall into one of 88 designated areas called constellations. The people, animals, and objects the constellations represent are mythological and historical holdovers. Neither astronomers nor celestial cartographers have invented a new constellation for 250 years.

Studying stars

Taken as individual objects, stars become targets for scientific research. Once astronomers determine a star's position, they measure its apparent brightness — how bright the star looks. But they also want to know a star's luminosity — its real brightness independent of its distance from Earth. To find this quantity, they must know the star's distance.

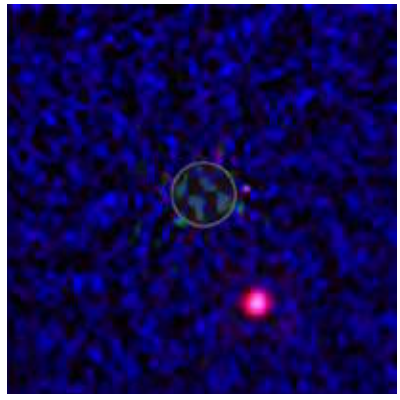
A shift called parallax provides distances to several thousand of the nearest stars. Astronomers measure parallax by imaging the star twice, with 6 months between images. This provides a baseline double the Earth-Sun distance, and the angle measured against more remote objects allows a straightforward conversion to the star's distance.

Astronomers also determine how fast a star moves across our line of sight — and in which direction — by studying images of the star taken years apart. Nearby stars move with respect to stars that lie farther away (or, if the star is in a fortuitous location, with respect to even more distant objects like galaxies, which lie far beyond the stars we see).



▲ STAR-FORMING REGION N159 lies 170,000 light-years away in one of our satellite galaxies, the Large Magellanic Cloud (LMC). This Hubble WFPC2 image shows torrential stellar winds from hot, newborn massive stars within the nebula sculpting ridges, arcs, and filaments in the vast cloud, which measures more than 150 light-years across.

This observation is part of a search for young, massive stars in the LMC. It's rare for astronomers to see massive stars so early after their birth. The red in this true-color image comes from light emitted by ionized hydrogen, and the yellow is from ionized oxygen. M. HEYDARI-MALAYERI (PARIS OBSERVATORY)/NASA/ESA



▲ A BROWN-DWARF STAR — 2MASSWJ 1207334–393254 — is the red object below center in this Hubble NICMOS image. A companion planet (circled) with 5 times Jupiter's mass lies nearby.

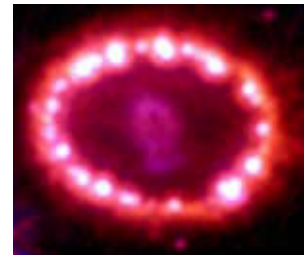
The glare of the dwarf, which is 700 times brighter than the planet candidate (at Hubble's near-infrared sensitivity) has been reduced through image processing. In this picture, the dwarf and candidate planet lie at least 5 billion miles (8 billion km) apart.

NASA/ESA/G. SCHNEIDER (UNIV. OF ARIZONA)

▲ DWARF IRREGULAR GALAXY NGC 1705's center blazes with the light of thousands of young and old stars. Seventeen million light-years away, NGC 1705 is an ideal laboratory to investigate star-formation history.

Young, hot, blue stars concentrate toward this galaxy's center, while older, cooler, red stars are more spread out. This galaxy has been forming new stars throughout its lifetime, but a burst of star formation occurred as recently as 26 to 31 million years ago.

NASA/ESA/THE HUBBLE HERITAGE TEAM (AURA/STScI)



▲ SN 1987A was the brightest stellar explosion seen since the one Johannes Kepler observed 400 years ago. Although the supernova itself is now a million times fainter than in 1987, a new show in the space surrounding it has begun.

This image, taken by Hubble's Advanced Camera for Surveys, shows many bright spots along a ring of gas, like pearls on a necklace. These cosmic "pearls" resulted as a supersonic shock wave, unleashed during the explosion, slammed into the ring at more than 1 million mph (1.6 million km/h). The collision heats the gas ring, causing its innermost regions to glow.

Astronomers detected the first "hot spot" in 1996, but now they see dozens of them all around the ring. The ring, which measures about a light-year across, already existed when the star exploded. Astronomers believe the star shed the ring about 20,000 years before the supernova blast. NASA/P. CHALLIS/R. KIRSHNER (HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS)/B. SUGERMAN (STScI)

▲ **THIS UNUSUAL IMAGE** displays a rare view of a 35-light-year-diameter cavity carved by the outflow of matter and intense ultraviolet radiation from a young star. The nebula astronomers call N44F arose from an exceptionally hot star once buried in a cold, dense cloud. A torrent of fast-moving particles — a stellar wind — sculpts this object.

The central star ejects more than 100 million times more mass than our Sun ejects per second. The particles move about 4 million mph (7 million km/h).

The nebula N44F is one of a handful of known interstellar bubbles. Astronomers have observed bubbles like this around evolved massive stars and also around clusters of stars but rarely around isolated stars, as with N44F.

This region harbors additional surprises as well. Several 4- to 8-light-year-high columns of cool dust and gas line its interior wall. Blistering ultraviolet radiation from the central star created the columns. Like windsocks, they point in the direction of the energy flow. These pillars look small in this image only because they lie about 160,000 light-years away in our neighboring dwarf galaxy, the Large Magellanic Cloud. NASA/ESA/Y. NAZÉ (UNIV. OF LIÉGE, BELGIUM)/ Y.-H. CHU (UNIV. OF ILLINOIS)

Going deeper

Most of the information a star reveals comes when astronomers take its spectrum. A spectrum is starlight broken down into its component colors, like a rainbow formed when sunlight passes through water droplets. Stellar spectra add one additional component to the rainbow, however.

Crossing all stellar spectra are dark marks called absorption lines. By studying the strengths, widths, and positions of these lines, astronomers can tell a lot about a star.

Absorption lines form when chemical elements in a star's atmosphere absorb radiation from the star's core (where all stellar energy is generated). Because specific atoms absorb only certain wavelengths — and some only at the right temperatures — a stellar "fingerprint" forms.

Astronomers compare stellar spectra to spectra they generate in the laboratory. So, by experimentation, they've discovered where dark lines form for all possible elements in a star's atmosphere. The first thing a spectrum tells an astronomer, therefore, is the star's chemical composition.

Just about every star comprises mostly hydrogen and helium. The hydrogen/helium mix is about 3:1. This ratio mirrors that of the universe.

Elements heavier than helium, called metals, form less than 1 percent of the cosmos. The lighter of the 92 naturally occurring elements — calcium, carbon, aluminum, and others as heavy as iron — form as by-products of nuclear fusion (see "Fusion cooking," page 32), and astronomers detect them in spectra. The other 64 elements formed in a different way.

◄ **A SUPERNOVA** in the Small Magellanic Cloud has begun to dissipate its interior into a spectacular display of colorful filaments.

The supernova remnant (SNR), known as 1E0102.2–7219, or E0102 for short, is the blue shell of debris just below center. It lies almost 50 light-years from the edge of the massive star-forming region N76, also known as Henize 1956, the large reddish cloud in the upper right of the image.

The composition, and, thus, the coloring, of the SNR in comparison to its star-forming neighbor is due to the presence of large quantities of oxygen compared to hydrogen. E0102 is a member of an oxygen-rich class of SNRs that shows an absence of hydrogen and helium.

One explanation for the abundance of oxygen in the SNR is that the parent star was massive and old; it had fused most of its core hydrogen into heavier elements and blown away most of its atmospheric hydrogen as stellar wind before it exploded. Astronomers estimate the SNR is only about 2,000 years old. E0102 is relatively young on astronomical scales and is just beginning its interactions with the nearby interstellar medium. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

▲ **NGC 604** is one of the largest known regions of star formation in a nearby galaxy. This monstrous stellar nursery contains more than 200 brilliant blue stars within a cloud of glowing gases 1,300 light-years across.

The bright stars in NGC 604 are young by astronomical standards, having formed a mere 3 million years ago. Most of the brightest and hottest stars form a loose cluster in a cavity near the nebula's center. Stellar winds from these hot, blue stars, along with supernova explosions, carved out the hole at the center.

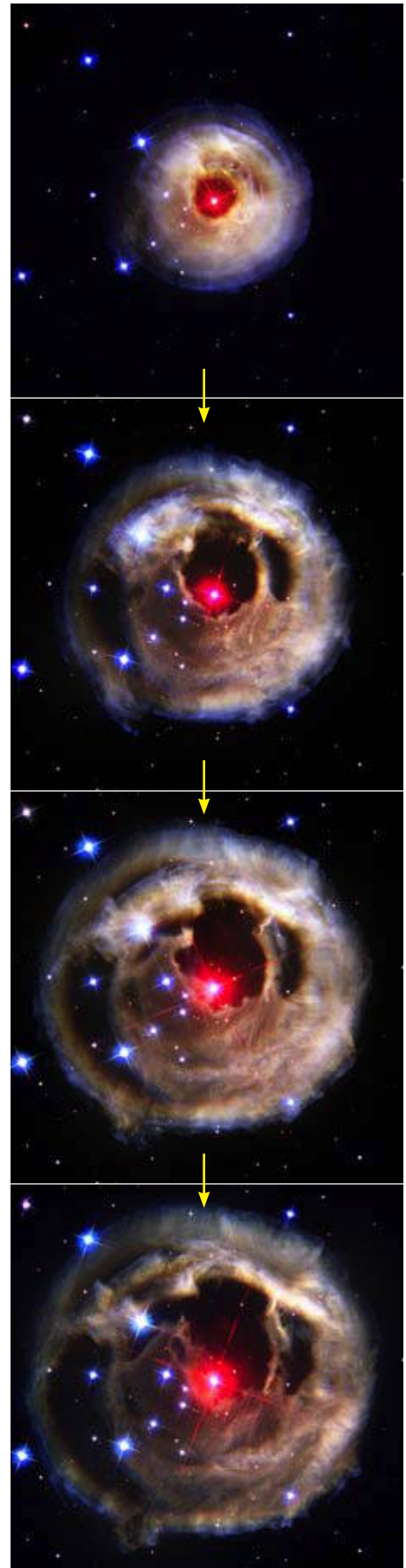
The most massive stars in NGC 604 exceed 120 times the Sun's mass, and their surface temperatures reach 40,000 K. Ultraviolet radiation floods out from these hot stars, making the surrounding nebular gas fluoresce.

NGC 604 lies in a spiral arm of the nearby Pinwheel Galaxy (M33), located about 2.7 million light-years away within the northern constellation Triangulum. NASA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

▲ **INTRICATE WISPS** of glowing gas float amid myriad stars in this image created by combining data from Hubble and the Chandra X-ray Observatory. The gas is supernova remnant N132D, ejected 3,000 years ago by the explosion of a massive star in the Large Magellanic Cloud.

Deep within the remnant, the Hubble visible-light image reveals a crescent-shaped cloud of pink-hued emission from hydrogen, and soft purple wisps that correspond to regions of glowing oxygen emission. The large horseshoe-shaped gas cloud to the left of the remnant glows in X rays.

In order to emit X rays, the gas must have been heated to about 10 million Kelvin in the explosion. A supernova-generated shock wave traveling at more than 4 million mph (6.4 million km/h) continues to propagate through the low-density medium today. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



► **THIS SEQUENCE** from Hubble's Advanced Camera for Surveys demonstrates the reverberation of light through space caused by an unusual stellar outburst. This image sequence from May to December 2002 shows changes in the appearance of the dust surrounding this star as different parts are illuminated sequentially.

Astronomers call this reflection effect a "light echo." From the top to the bottom image, the nebula grows from 4 to 7 light-years across. The red star at the center of the eyeball-like feature is an unusual erupting supergiant called V838 Monocerotis, located about 20,000 light-years away in the constellation Monoceros the Unicorn. During its outburst, the star brightened to more than 600,000 times our Sun's brilliance.

Each of the four images represents a 1.8-hour exposure taken with the Advanced Camera for Surveys. NASA/ESA/H. E. BOND (STScI)

Ka-boom!

Elements heavier than iron can't form by nuclear fusion because not enough energy is available. Even the most massive star, with a core temperature more than 2.8 billion Kelvin, runs into a roadblock at iron. So, to create elements like tin, iodine, and gold, a star must become a supernova.

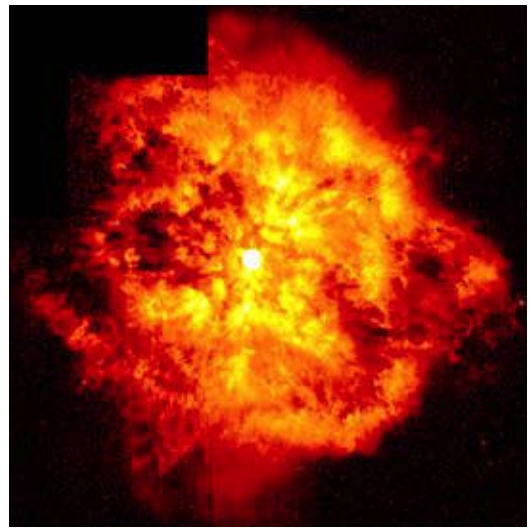
As a star proceeds through its life, it uses up the nuclear fuel contained in its core. For example, much less hydrogen will exist in the Sun's core several billion years from now. As this fuel supply diminishes, the core will cool, throwing the Sun out of balance.

In stable stars like the present-day Sun, radiation from the core balances gravity's inward pull. But if the radiation decreases, gravity shrinks the star. When this happens, the core's density and temperature rise dramatically, and helium — the "ash" left from hydrogen fusion — begins to fuse.

The energetic core produces much more energy, swelling the star into a red giant — a star several hundred times larger than the present-day Sun. The Sun's atmosphere will one day engulf Mercury, Venus, and perhaps Earth.

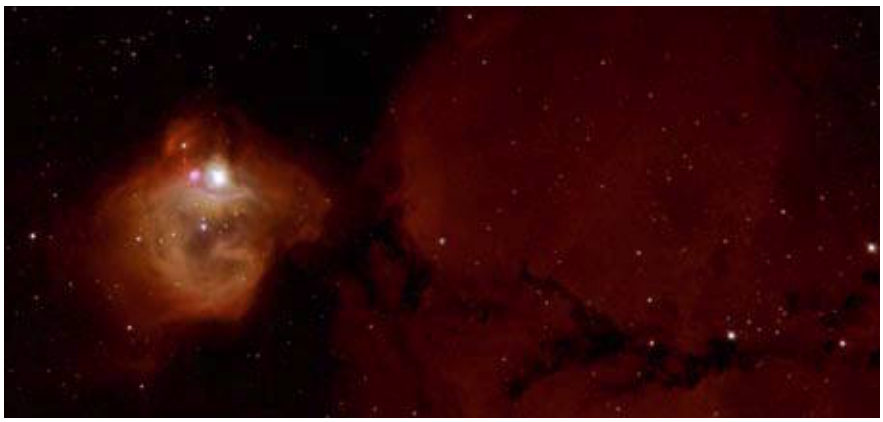
For Sun-like stars, the process doesn't go much further. Eventually, the core contracts to a dense object — called a white dwarf — about Earth's size, and the star's outer layers gently move away from the core.

For stars that begin life with roughly 8 times the Sun's mass, however, the end is much more dramatic. Such stars end their lives as supernovae — among the universe's biggest explosions. And it's these explosions that create heavy elements and distribute them throughout the cosmos.



▲ **LIKE FIREWORKS,** this dramatic Hubble WFPC2 image of the energetic star WR124 reveals it is surrounded by hot clumps of gas being ejected into space at speeds greater than 100,000 mph (161,000 km/h). The vast arcs of glowing gas are filamentary, chaotic substructures — 100-billion-mile-wide glowing gas blobs. Each blob contains about 30 times Earth's mass.

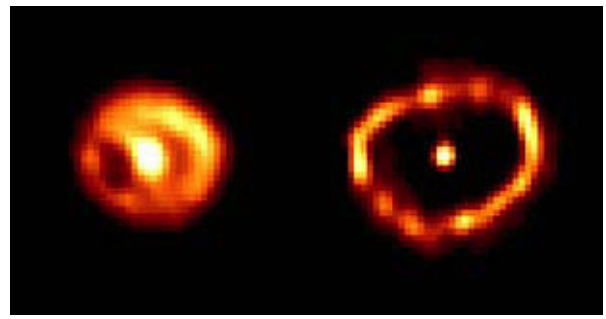
The hot central star is a Wolf-Rayet type going through a violent, transitional phase. Astronomers estimate the surrounding nebula is no older than 10,000 years, too young to have slammed into the gasses surrounding it. The star lies 15,000 light-years away in Sagittarius. YVES GROSDIDIER (UNIV. OF MONTREAL AND OBSERVATOIRE DE STRASBOURG)/ANTHONY MOFFAT (UNIV. OF MONTREAL)/GILLES JONCAS (UNIV. LAVAL)/AGNES ACKER (OBSERVATOIRE DE STRASBOURG)/NASA



▲ **INTENSE RADIATION** from newborn, ultra-bright stars has blown a glowing spherical bubble in the nebula N83B, also known as NGC 1748. This Hubble WFPC2 image shows a compact star-forming region in a small part of the Large Magellanic Cloud. The nebula's central star is actually about 30 times more massive and almost 200,000 times brighter than our Sun. The intense light and powerful stellar "winds" from this star have cleared away the surrounding gas to form a cavity approximately 25 light-years in diameter.

Astronomers estimate the radiation and stellar winds carved out the spherical void in N83B recently — maybe as little as 30,000 years ago.

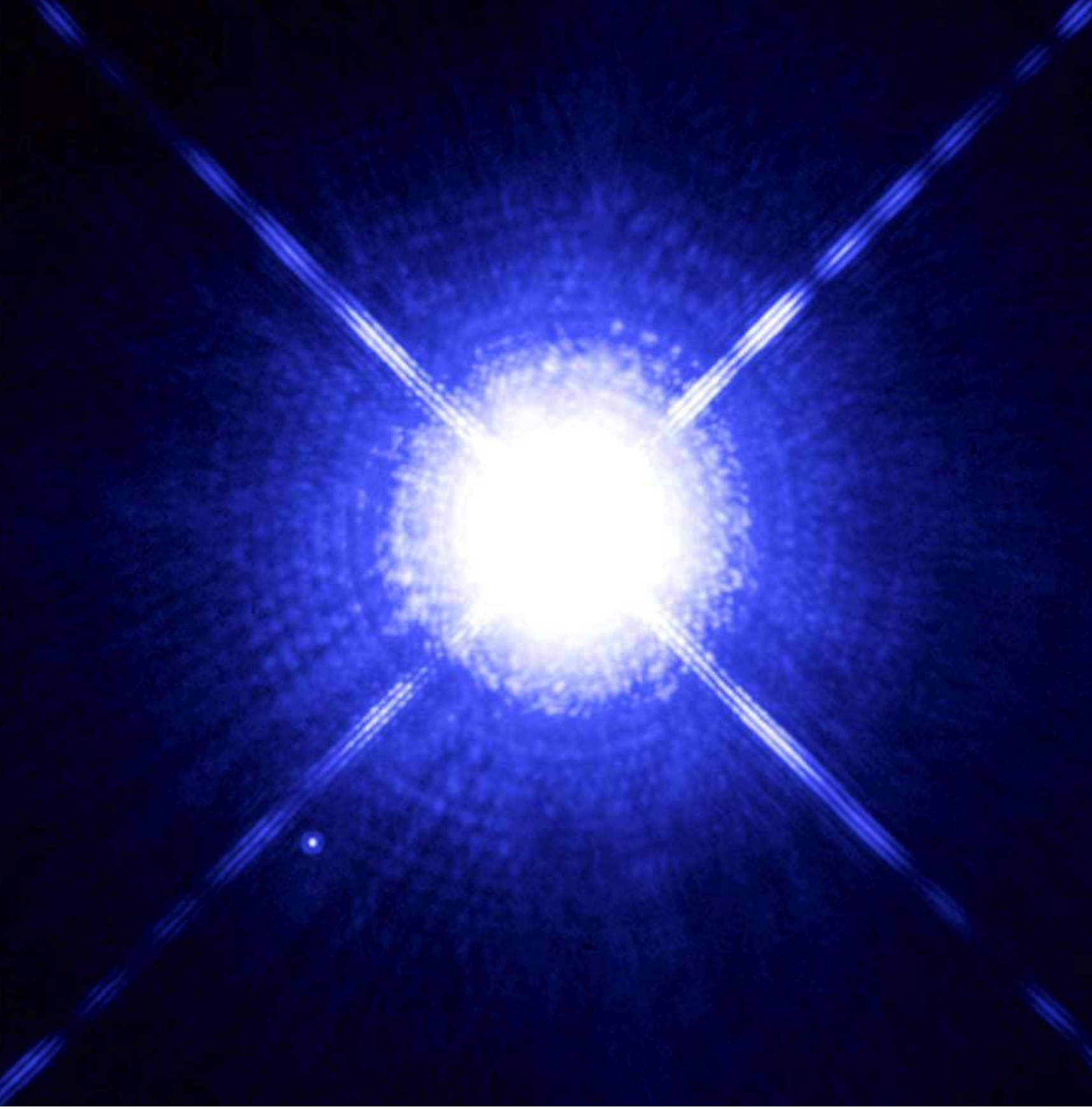
To the right of the glowing N83B lies a much larger, less energetic, diffuse nebula, known as DEM22d, partly obscured by an extended dust and gas lane. NASA/ESA/M. HEYDARI-MALAYERI (PARIS OBSERVATORY)



▲ **NOVA CYGNI 1992,** which erupted February 19, 1992, is rapidly ballooning gas blasted off a star. Hubble's Faint Object Camera has given astronomers their best look yet at this object.

A Hubble image taken May 31, 1993 (left), 467 days after the explosion, provided the first glimpse of the ring and a mysterious bar-like structure. The newer image (right), taken in 1994, reveals an elliptical and slightly lumpy ring-like structure. The ring forms the edge of a bubble of hot gas blasted into space by the nova.

A comparison of the images reveals the ring evolved in the 7 months between the two observations. The ring expanded from approximately 74 billion to 96 billion miles in diameter. The bar-like structure has disappeared. Nova Cygni is 10,500 light-years away in Cygnus. F. PARESCE/R. JEDRZEJEWSKI (STScI)/NASA/ESA



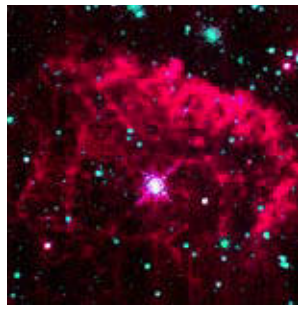
▲ **THE SKY'S** brightest star, Sirius (Alpha [α] Canis Majoris), is also a double star. American telescope-maker Alvan Graham Clark (1832–1897) discovered its duplicity in 1862 while testing a new telescope objective lens. This Hubble image shows both components. Sirius A, which blazes at magnitude –1.46 shines 10,000 times as bright as Sirius B, at magnitude 8.5. Sirius B was the first white-dwarf star discovered. A white dwarf is the remains of a Sun-like star's core that exhausted its nuclear fuel and collapsed to about the size of Earth.

NASA/H. E. BOND AND E. NELAN (STScI)/M. BARSTOW AND M. BURLEIGH (UNIV. OF LEICESTER, U. K.)/J. B. HOLBERG (UNIV. OF ARIZONA)

▲ **PLANETARY NEBULA** NGC 7027 resulted from the death of a Sun-like star. This Hubble NICMOS infrared image, combined with an earlier visible-light WFPC2 exposure, shows a young planetary nebula in a state of rapid transition. This image captured the young planetary nebula in a short evolutionary phase, lasting perhaps 1,000 years. During this phase, intense ultraviolet radiation from the central star lights up the gas surrounding it.

Encircling this hot gas is a cloud of dust and cool molecular hydrogen that can be seen only in infrared light. The gas (which appears white) simmers at tens of thousands of degrees Fahrenheit.

NGC 7027 is one of the smallest objects of its kind to be imaged by Hubble. However, the region seen here is approximately 14,000 times the average distance between Earth and the Sun. NGC 7027 lies 3,000 light-years away in Cygnus. WILLIAM B. LATTER (SIRTF SCIENCE CENTER/CALTECH)/NASA



▲ **THE BRIGHT WHITE DOT** seen here is one of our galaxy's intrinsically brightest stars. Hubble's NICMOS took the picture because the star lies at the galactic center, behind obscuring dust.

NICMOS' infrared vision penetrated the dust to reveal the star, which glows with the radiance of 10 million Suns. The image also shows one of the most massive stellar eruptions ever seen.

The radiant star has enough raw power to blow off two expanding shells (magenta) of gas equal to the mass of several Suns. The largest shell is so big (4 light-years) it would stretch nearly all the way from our Sun to the next nearest star.

Despite such a tremendous mass loss, astronomers estimate the extraordinary star may be 100 times more massive than our Sun, and may have started with as much as 200 solar-masses. The star lies 25,000 light-years away in the constellation Sagittarius. DON F. FIGER (UCLA)/NASA

◄ **THE ORION NEBULA** (M42) is a stellar nursery where Hubble uncovered a swarm of about 50 newborn brown dwarfs. The brown dwarfs are too dim to be seen in visible-light images.
That's because the young stars are embedded in dense clouds of dust and gas. Hubble's NICMOS penetrated those clouds to capture this view. The brown dwarfs are the image's faintest objects and have masses equaling 10 to 80 Jupiters. NEAR-INFRARED IMAGE: NASA/K. L. LUHMAN (HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS)/G. SCHNEIDER, E. YOUNG, G. RIEKE, A. COTERA, H. CHEN, M. RIEKE, AND R. THOMPSON (STEWARD OBSERVATORY, UNIV. OF ARIZONA); VISIBLE-LIGHT IMAGE: NASA/C. R. O'DELL AND S. K. WONG (RICE UNIV.)

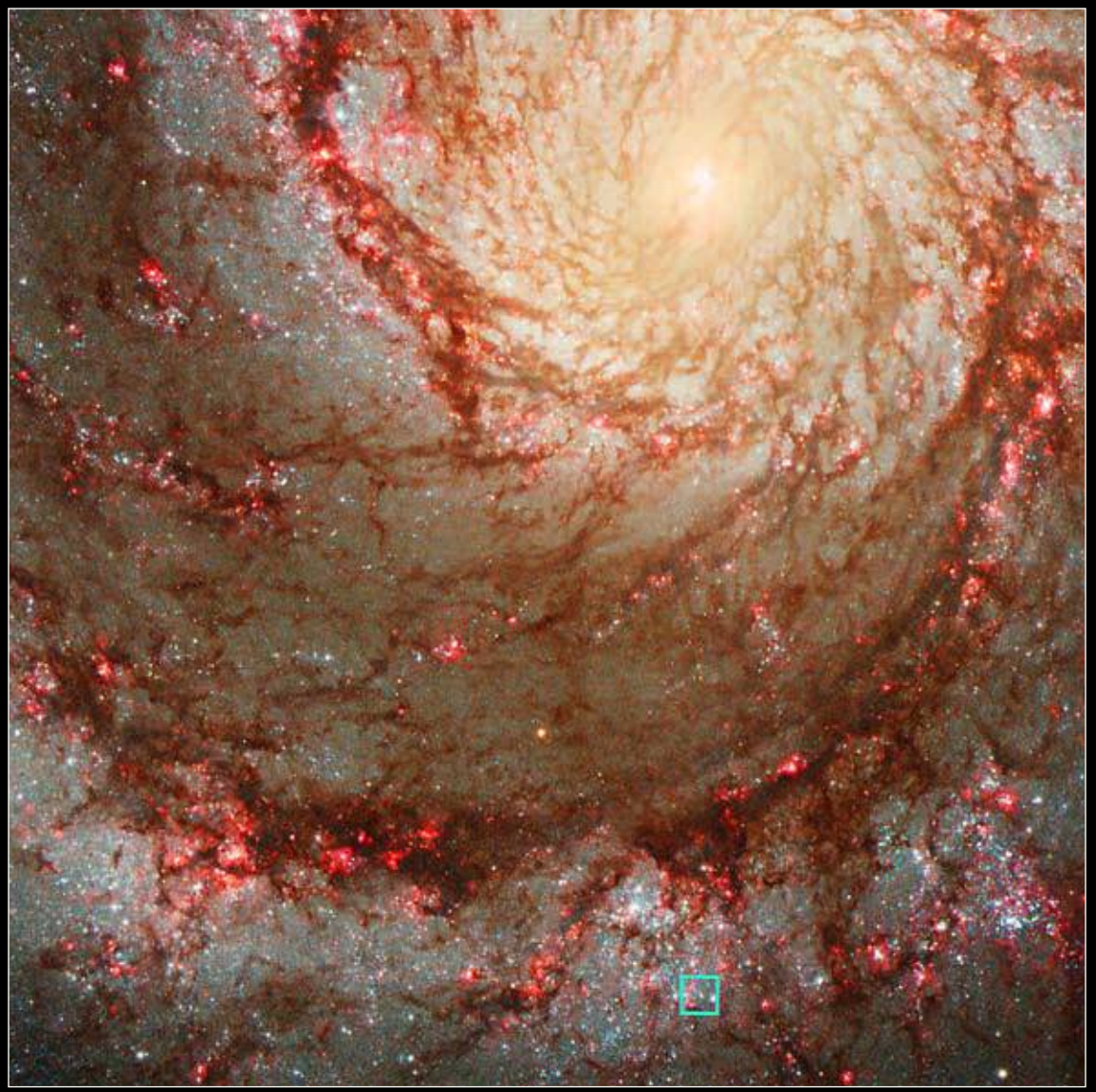
▲ **THE VEIL NEBULA** (NGC 6990/2/5) is a supernova remnant. It marks the edge of an expanding blast wave from a colossal stellar explosion that occurred about 15,000 years ago.

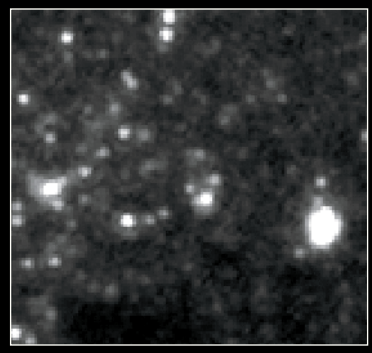
As the supernova's blast wave slams into tenuous clouds of interstellar hydrogen, the collision heats and compresses the gas, which emits light of specific colors as it cools.

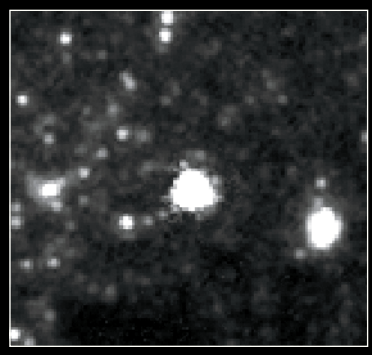
Hubble's detailed image shows the blast wave overrunning dense clumps of gas. Although Hubble can reveal details about as small as our solar system, the clumps remain unresolvable. A blue ribbon of light stretching across the picture might be a knot of gas ejected by the supernova.

This interstellar "bullet" travels more than 3 million mph (5 million km/h). It is just catching up with the shock front, which has been slowed by plowing into interstellar material.

The Veil Nebula appears as a faint ring of glowing gases about 3° across in the constellation Cygnus the Swan. The supernova remnant lies 2,600 light-years away. Hubble's Wide Field and Planetary Camera took this image April 24, 1991. J. HESTER (ARIZONA STATE UNIV.)/NASA







IN THE WHIRLPOOL GALAXY (M51), a massive star abruptly ends its life in a brilliant flash of light. Hubble's Advanced Camera for Surveys snapped images of the exploding star, called supernova (SN) 2005cs, 12 days after its discovery. Astronomers then compared those photos with Hubble images of the same region before the supernova blast to pinpoint the star that exploded.

The left image shows a section of M51. The small square marks the region where the progenitor star — the star that became the supernova — resides.

The upper-right image shows the region prior to the supernova. The lower-right image displays SN 2005cs (the central bright object). The star was a red supergiant with a mass between 7 and 10 solar-masses. NASA/ESA, W. LI AND A. FILIPPENKO (UNIV. OF CALIFORNIA, BERKELEY)/S. BECKWITH (STScI)/THE HUBBLE HERITAGE TEAM (STScI/AURA)

The afterlife

When a star dies, three possible "corpses" can form. A star's fate depends on one thing: its mass. When a star like the Sun, or one with several times the Sun's mass, dies, its outer layers expand to form a planetary nebula. The core, now no longer producing energy by nuclear reactions, shrinks to about the size of Earth. The object is a white dwarf.

White dwarfs are dense and hot. They can contain up to 1.4 solar-masses, and their surfaces measure in the tens of thousands of degrees Fahrenheit. Because they are so dense, it will take roughly a trillion years for the star to radiate all its heat away. After that, it will drift through space as a black dwarf.

Stars born with 8 times the Sun's mass, or more, will explode as supernovae. In this scenario, the star's core experiences some drastic forces. In fact, electrons, which usually orbit far from the centers of atoms, are crushed into the nuclei, where they combine with protons. The electrons' negative charges

cancel the protons' positive charges, and the resulting neutrons can crowd into a much smaller space. Such a neutron star may have 3 times the Sun's mass in a sphere measuring 10 miles (16 km) across.

Trying to imagine a neutron star's density is difficult. A white dwarf's material has a density of approximately 1 ton per cubic centimeter (16.4 tons per cubic inch). That's pretty heavy stuff. A neutron star's density, however, is vastly greater. One cubic centimeter of a neutron star weighs 400 million tons (6.6 billion tons per cubic inch).

Some neutron stars develop hot spots on their surfaces, probably related to their magnetic fields. If the star rotates in such a way that the hot spots pass our field of view, the star pulses in brightness. Astronomers call such rotating neutron stars "pulsars."

Neutron stars, the second possible fate for stars, certainly are strange. But the strangest stellar corpse — and possibly the universe's strangest object overall — is a black hole.

Black holes represent regions where gravity has overwhelmed every other force. Black holes form when the most massive stars (those with more than 8 times the Sun's mass) become supernovae.

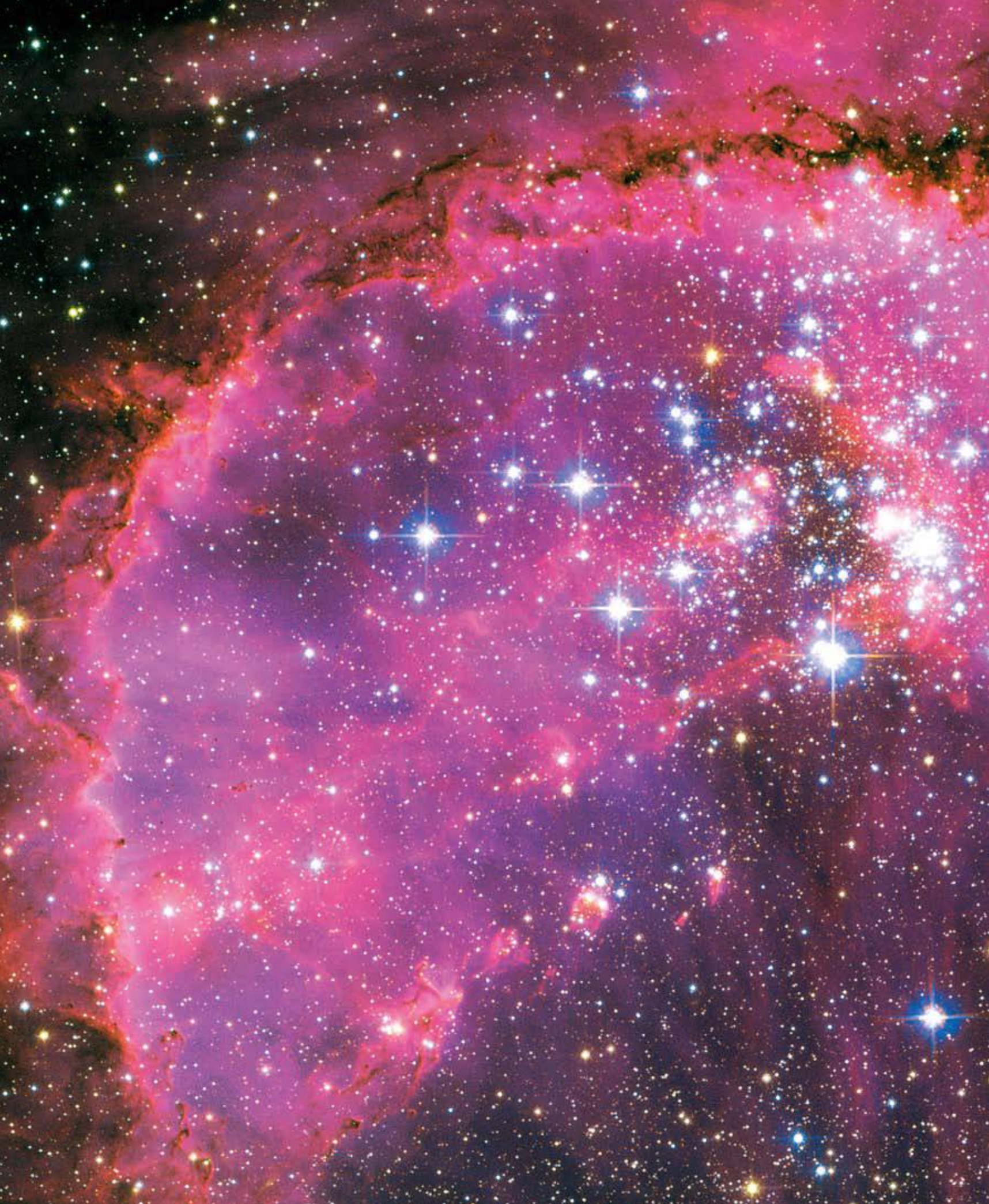
At the end of its life, such a massive star's surface swells and it becomes a supergiant, with a diameter that may exceed a billion miles. When the incredibly hot core finally stops producing enough energy to maintain the star's size, stellar material rushes in, and the star explodes. The core collapses beyond the limit of a neutron star until it becomes a singularity — a place where the density is infinite.

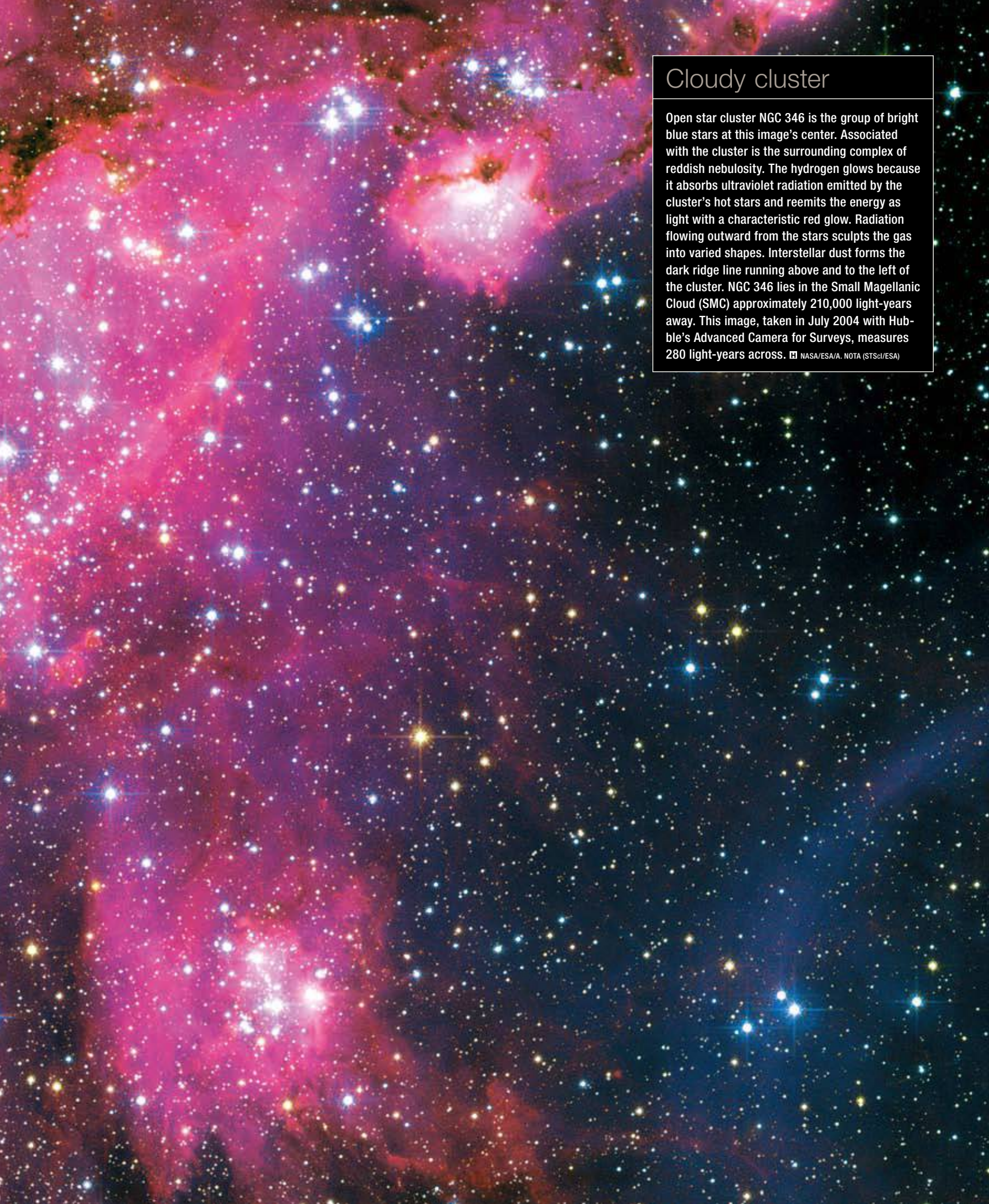
Nothing, not even light, can escape the gravitational pull of a black hole. Any matter that falls into a black hole disappears forever.

The existence of black holes no longer is in question. Although astronomers will never "see" a black hole, they can study the effects of these enigmatic objects. Hubble has captured all these stages of stellar evolution. The space telescope has helped scientists piece together a more complete picture of stars' lives — and deaths. H

◄ **THE EXPLOSION** of a massive star blazes with the light of 200 million Suns in this Hubble Advanced Camera for Surveys image. The arrow at top right points to the stellar blast, called a supernova.

The supernova is so bright in this image that it easily could be mistaken for a foreground star in our Milky Way. And yet, this supernova, called SN 2004dj, resides in the outskirts of NGC 2403, a galaxy located 11 million light-years from Earth in the constellation Camelopardalis. NASA/ESA/A. V. FILIPPENKO (UNIV. OF CALIFORNIA, BERKELEY)/P. CHALLIS (HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS)





Cloudy cluster

Open star cluster NGC 346 is the group of bright blue stars at this image's center. Associated with the cluster is the surrounding complex of reddish nebulosity. The hydrogen glows because it absorbs ultraviolet radiation emitted by the cluster's hot stars and reemits the energy as light with a characteristic red glow. Radiation flowing outward from the stars sculpts the gas into varied shapes. Interstellar dust forms the dark ridge line running above and to the left of the cluster. NGC 346 lies in the Small Magellanic Cloud (SMC) approximately 210,000 light-years away. This image, taken in July 2004 with Hubble's Advanced Camera for Surveys, measures 280 light-years across. NASA/ESA/A. NOTA (STScI/ESA)

A thousand points

Star clusters paint a picture of star formation by the numbers.

Stars form from vast clouds of dust and cold gas called nebulae. Over millions of years, gravity slowly contracts nebulae until the pressures and temperatures at the centers of these vast clouds are right for nuclear fusion and, thus, star formation. But stars do not form alone.

A nebula with enough gas to equal the Sun's mass cannot begin to contract because that amount of material doesn't have enough self-gravity to start the process. A nebula's mass must equal approximately 1,000 solar-masses for contraction to start.

The sky's best-known nebula, the Orion Nebula (M42), which lies in the sword of the constellation Orion the Hunter and is visible to the unaided eye, contains a mass of several thousand Suns. In 20 million years or so, the nebula will be replaced by a blazing cluster of stars.

# of light

▲ **LH 95** is one of the hundreds of star-forming systems, called associations, located in the Large Magellanic Cloud. This region shows both low-mass, infant stars and their more massive stellar neighbors.

The largest stars in LH 95 — those with at least 3 solar-masses — generate strong stellar winds and radiation that reflects off the surrounding interstellar gas. The result is a bluish nebula of expanding hydrogen. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

◄◄ **GLOBULAR** clusters sort out stars by their masses, according to data astronomers collected with Hubble's Advanced Camera for Surveys. More massive stars slow down and sink to the cluster's core, while lighter stars pick up speed and move across the cluster to its periphery.

The European Southern Observatory's Very Large Telescope in Chile took the photo at left of globular star cluster 47 Tucanae (NGC 104), one of the densest globular clusters in the Southern Hemisphere. The cluster contains approximately a million stars and lies roughly 15,000 light-years away.

At right, one of many Hubble images of 47 Tuc's core allowed astronomers to track the stars' "beehive swarm" motion. Researchers obtained precise velocities for nearly 15,000 stars in this cluster. GROUND IMAGE: VERY LARGE TELESCOPE/R. KOTAK AND H. BOFFIN (ESO); HUBBLE IMAGE: NASA/ESA/G. MEYLAN (ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE)

Different strokes

Astronomers categorize star clusters into three basic types. Open clusters are loose, irregular collections of hundreds to thousands of stars. They form in nebula-rich areas of the Milky Way (and other similar galaxies), especially along the spiral arms of these objects. Open clusters typically measure 10 light-years across.

Larger, less-populous star clusters are known as associations. These stellar groupings resemble open clusters but usually hold only up to 100 recently formed stars. Associations also span much greater diameters than open clusters. Associations may measure 100 light-years across, and the combined gravity of their stars can't hold them together. Astronomers believe associations last only a few tens of millions of years before the individual stars go their separate ways.

Open clusters also eventually dissolve, but they last much longer. Their life spans are typically hundreds of millions to a billion years. Astronomers believe our Sun formed in such a manner.

Open clusters dissolve into single- or multiple-star systems mainly because of interactions between stars in the cluster. If the individual motions of two stars in an open cluster, for example, bring them close together, they may be thrown from the cluster by a gravitational slingshot effect.

Hubble has imaged hundreds of open clusters and associations. By capturing these groups at various stages of evolution, Hubble has helped astronomers pin down the mechanism by which stars form.

▲ **HODGE 301** — a cluster of brilliant, massive stars — lies in an active starburst region. The cluster, which occupies the lower-right corner of this image, lies inside the Tarantula Nebula (NGC 2070) in one of our galaxy's satellites, the Large Magellanic Cloud, in Dorado.

Many of the stars in Hodge 301 have already evolved and exploded as supernovae. These stars are blasting material into the surrounding region at speeds of almost 720,000 mph (1.17 million km/h). The high-speed ejecta plow into the surrounding nebula, shocking and compressing the gas into a multitude of sheets and filaments. Near the center of the image lie small, dense gas globules and dust columns where new stars are forming. THE HUBBLE HERITAGE TEAM (AURA/STScI/NASA)

◄ **THE ARCHES** Cluster in the constellation Sagittarius outshines most other star clusters in our Milky Way. With a mass equivalent to more than 10,000 stars like our Sun, the monster cluster is 10 times more massive than typical young star clusters. Using Hubble to study the Arches, astronomers have established a stellar-mass limit.

Astronomers used Hubble's Near Infrared Camera and Multi-Object Spectrometer to study hundreds of stars in the Arches ranging from 6 to 130 solar-masses. The Arches Cluster is a youngster, about 2 to 2.5 million years old, and resides 25,000 light-years away in our galaxy's hub, a hotbed of massive star formation. In this rough-and-tumble region, huge gas clouds collide to form behemoth stars. At least a dozen of the cluster's stars weigh 100 solar-masses. DON FIGER (STScI)/NASA

► **GLOBULAR CLUSTER** M80 is one of the densest of the approximately 200 known globular star clusters in the Milky Way. Located about 28,000 light-years from Earth, M80 contains hundreds of thousands of stars held together by their mutual gravitational attraction.

Astronomers use globular clusters to study stellar evolution. All of the stars in the cluster formed at the same time, so they are the same age (about 13 billion years). The stars, however, cover a range of stellar masses.

Every star visible in this image is either more highly evolved than, or more massive than, our Sun. Especially obvious are the bright red giants, which are solar-mass stars nearing the ends of their lives.

This picture combines WFPC2 images from 1994, 1996, and 1997. THE HUBBLE HERITAGE TEAM (STScI/AURA)

▲ **THE STAR CLUSTER** NGC 1850, found in one of our neighboring galaxies, the Large Magellanic Cloud (LMC), is a young, globular-like open star cluster — a type of object unknown in our Milky Way. Moreover, NGC 1850 is surrounded by diffuse gas, which astronomers believe formed when massive stars exploded.

NGC 1850 lies in the LMC's bar and is the second-brightest star cluster in the LMC. The cluster's two components are both relatively young and consist of a main, globular-like cluster in the center and a younger, smaller cluster below and to the right, composed of extremely hot blue stars and fainter red T-Tauri stars. The main cluster is about 50 million years old; the smaller cluster only 4 million.

T-Tauri stars are Sun-like types so young they may have not started fusing hydrogen, which is how our Sun produces energy. Instead, they radiate energy released by their own gravitational contraction. Astronomers investigate these stars to learn about the births and lives of low-mass stars.

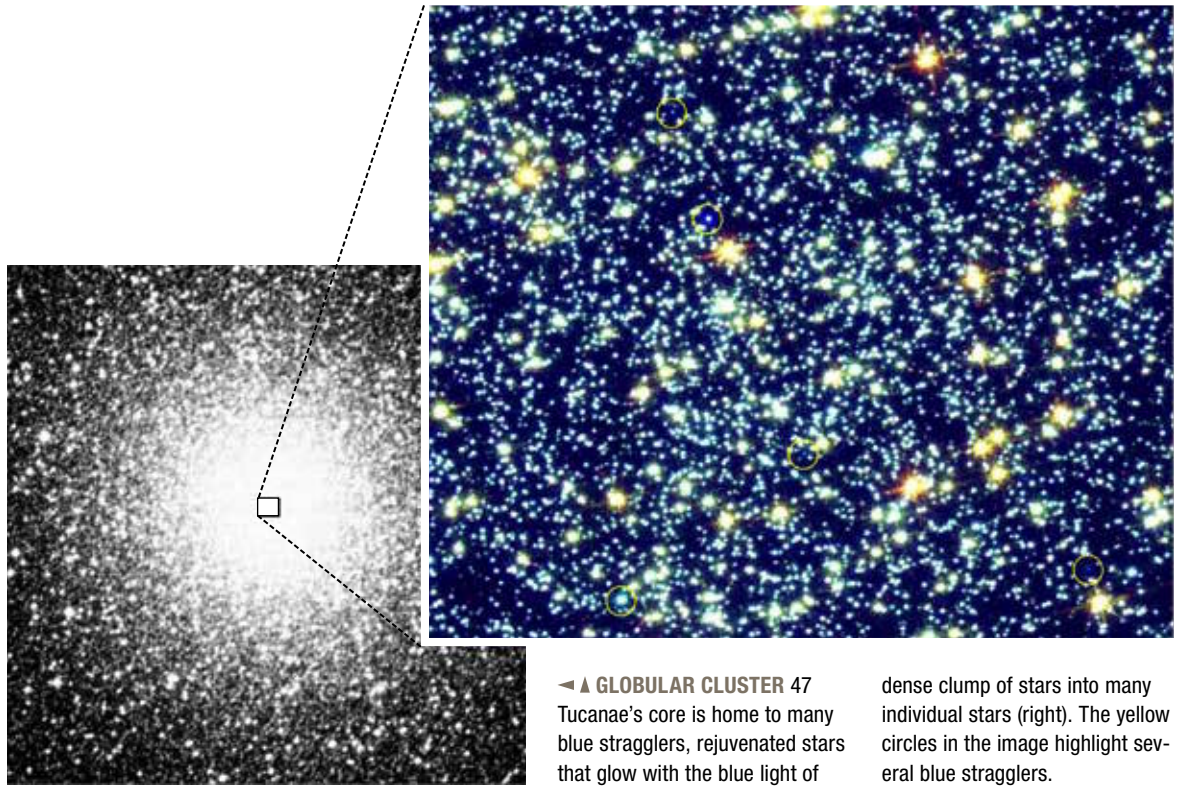
NASA/ESA/MARTINO ROMANIELLO (ESO, GERMANY)

Round and round

The other main star-cluster type is the globular cluster. These objects are spherical in shape, with the greatest concentration of stars toward their centers. Globular clusters contain many more stars than open clusters, with a range of about 10,000 to a million. At a globular's core, stars are packed 100,000 times more closely than in the Sun's neighborhood.

Globular clusters associated with the Milky Way are old objects. Most are older than 10 billion years. Because the stars formed so long ago from nebulae not enriched by supernovae, the stars of globulars contain only small amounts of metals (elements other than hydrogen and helium).

What really sets globular clusters apart, however, are their locations. Open clusters lie within the disk, or spiral arms, of our Milky Way and other spiral



◄▲ **GLOBULAR CLUSTER** 47 Tucanae's core is home to many blue stragglers, rejuvenated stars that glow with the blue light of young stars. A ground-based telescope image (left) shows the crowded core of 47 Tucanae, which lies 15,000 light-years away.

Hubble's Wide Field and Planetary Camera 2 separated the dense clump of stars into many individual stars (right). The yellow circles in the image highlight several blue stragglers.

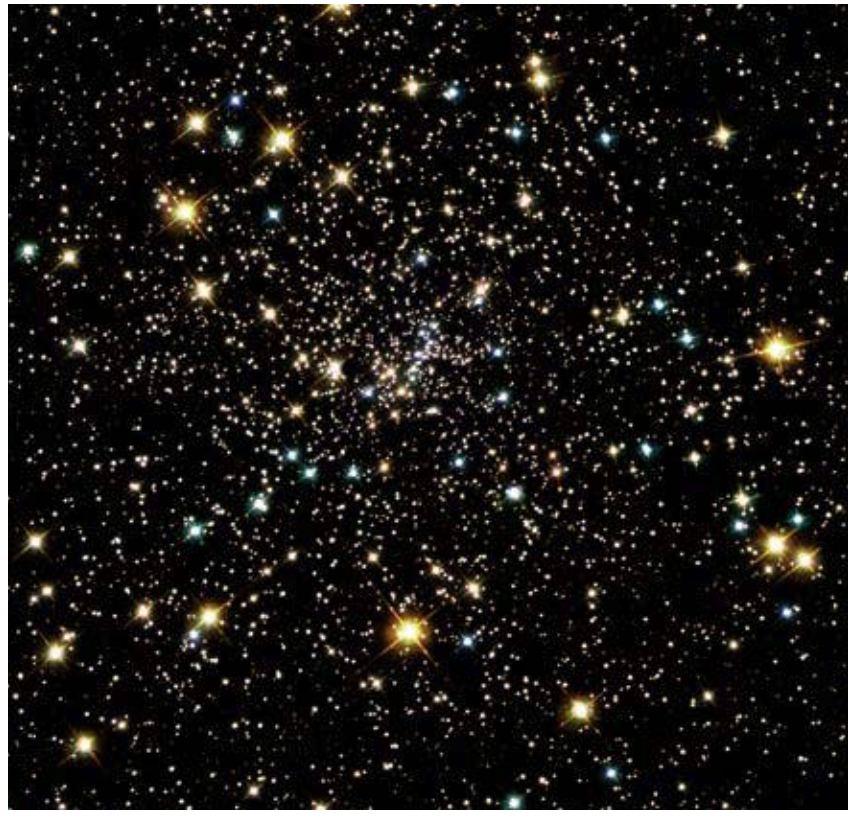
Astronomers theorize blue stragglers form either by the slow merger of stars in a double-star system or by the collision of two unrelated stars. R. SAFFER (VILLANOVA UNIV.)/ D. ZUREK (STScI)/NASA

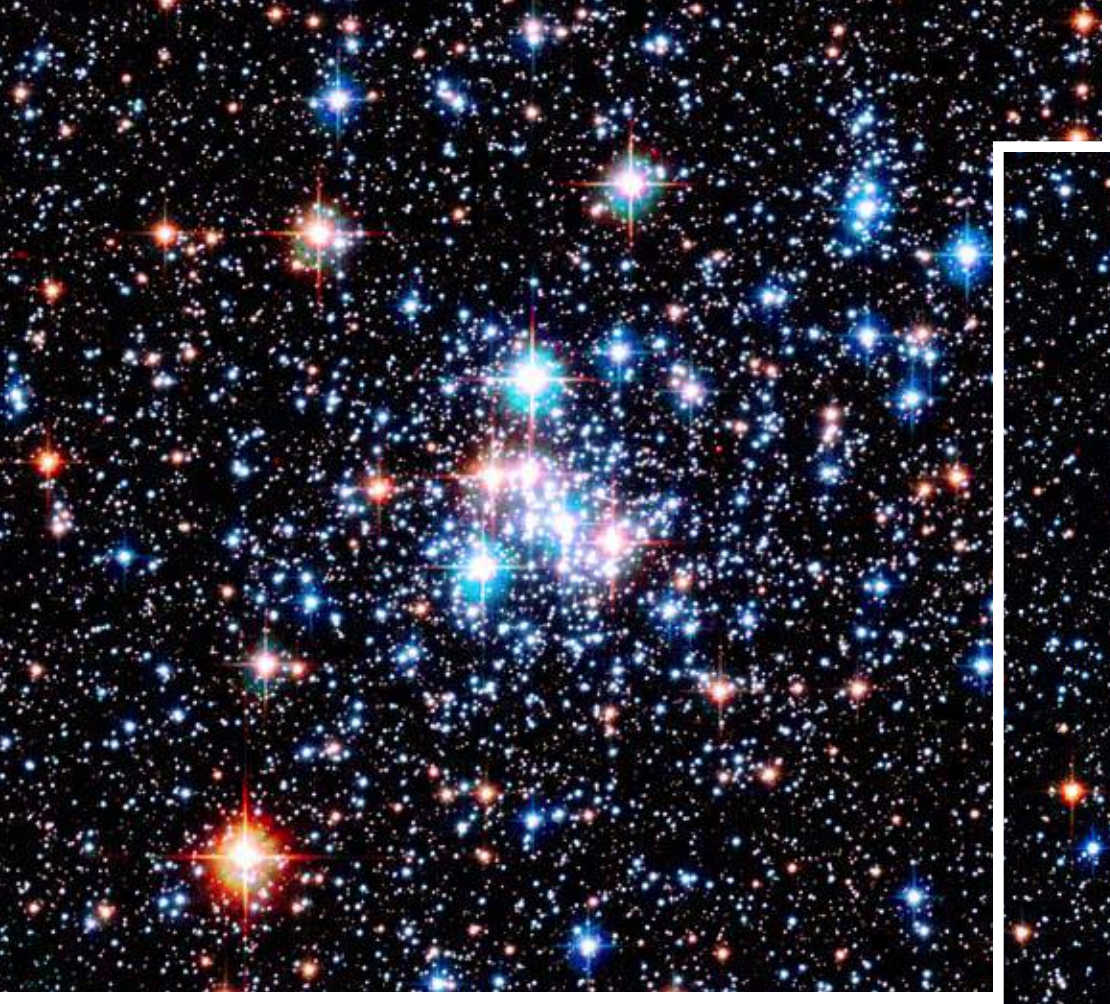
► **GLOBULAR CLUSTER** NGC 6397 in Ara the Altar looks, in this image, like an open star cluster. That's because, at only 8,200 light-years away, Hubble's Wide Field and Planetary Camera 2 peered deep into its core.

Actually, the stars lie close together. The stellar density is a million times greater than in our neighborhood. NGC 6397's stars lie only a few light-weeks apart, while the nearest star to our Sun is more than 4 light-years away.

These Hubble images were taken for a research program aimed at studying what is left behind when stars collide. When collisions occur, the two stars may merge to form a new star called a "blue straggler."

As bright, young stars, blue stragglers stand out among the old stars that make up most of a globular cluster's stars. Astronomers found several such bright blue stars near this object's center. NASA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



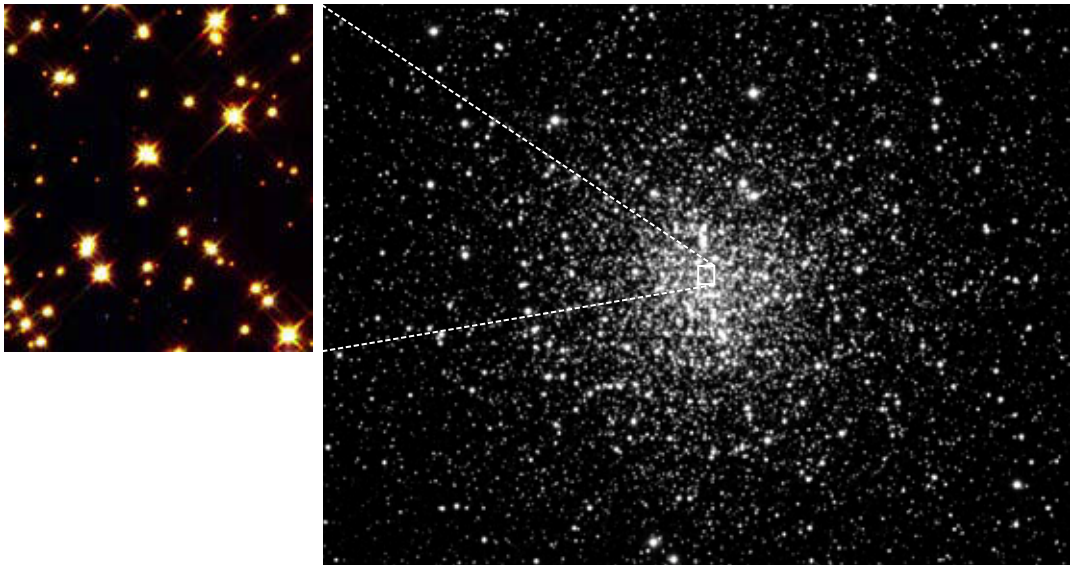


▲► **OPEN CLUSTERS** NGC 265 (above) and NGC 290 (right) lie in the Small Magellanic Cloud, about 210,000 light-years away. Each measures roughly 65 light-years across.

Gravity can hold star clusters together tightly, as is the case with densely packed crowds of hundreds of thousands of stars, called globular clusters. Open clusters — like the two shown here — can be loosely bound, irregularly shaped groupings of up to several thousand stars.

The stars in these open clusters are all relatively young and arose from the same interstellar gas cloud. They remain together only for a limited time and gradually disperse into space, pulled away by the gravitational tugs of other passing clusters and clouds of gas.

Most open clusters dissipate within a few hundred million years, whereas the more tightly bound globular clusters can exist for many billions of years. ESA/NASA



◄◄ **GLOBULAR CLUSTER** M4 (right) in Scorpius lies approximately 7,000 light-years away. When Hubble looked deep into M4 (left) astronomers discovered a large number of white-dwarf stars, which they may use to refine age estimates of the universe.

Hubble's observation was so sensitive that even the brightest white dwarf appeared fainter than a 100-watt lightbulb seen at the Moon's distance (239,000 miles). The inset image at left reveals 8 white dwarfs among the cluster's brighter population of yellow, Sun-like stars and cooler red-dwarf stars.

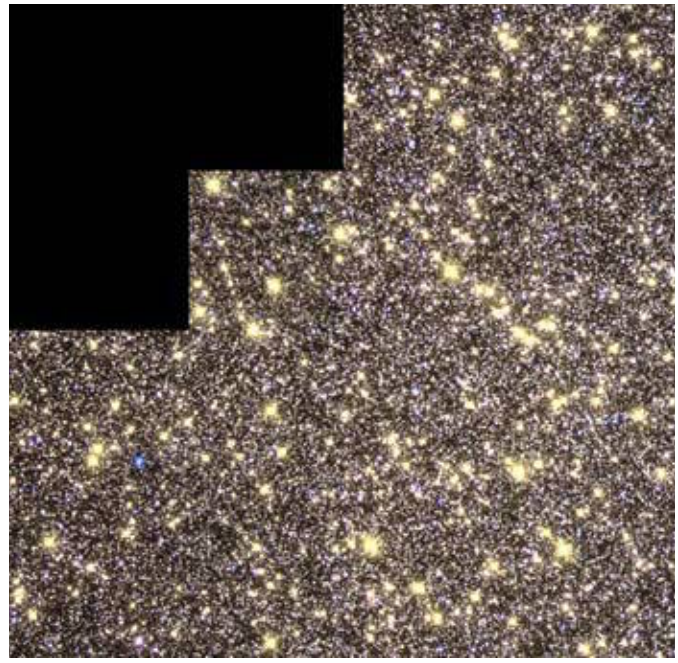
Hubble revealed 75 white dwarfs in one small area within M4. Astronomers predict the cluster contains a total of about 40,000 white dwarfs. The field of view spans 47 light-years.

GROUND IMAGE: KITT PEAK NATIONAL OBSERVATORY/NOAO/M. BOLTE; HUBBLE IMAGE: HARVEY RICHER (UNIV. OF BRITISH COLOMBIA)/NASA

galaxies. Globular clusters surround the Milky Way in a spherical distribution astronomers call the galactic halo.

By studying the distribution of globular clusters within the constellations Scorpius and Sagittarius, American astronomer Harlow Shapley (1885–1972) concluded that the Milky Way's center must lie in that direction. This finding removed Earth from the galaxy's center and placed it correctly along one of the Milky Way's spiral arms, roughly two-thirds out from the center.

Approximately 200 globular clusters surround our galaxy, but the Milky Way is not the only galaxy with these objects. Astronomers have observed globular clusters around all but the smallest galaxies. Generally, the more massive a galaxy, the more globular clusters orbit it. The giant elliptical galaxy M87 in Virgo, for example, contains more than 1,000 globular clusters. H

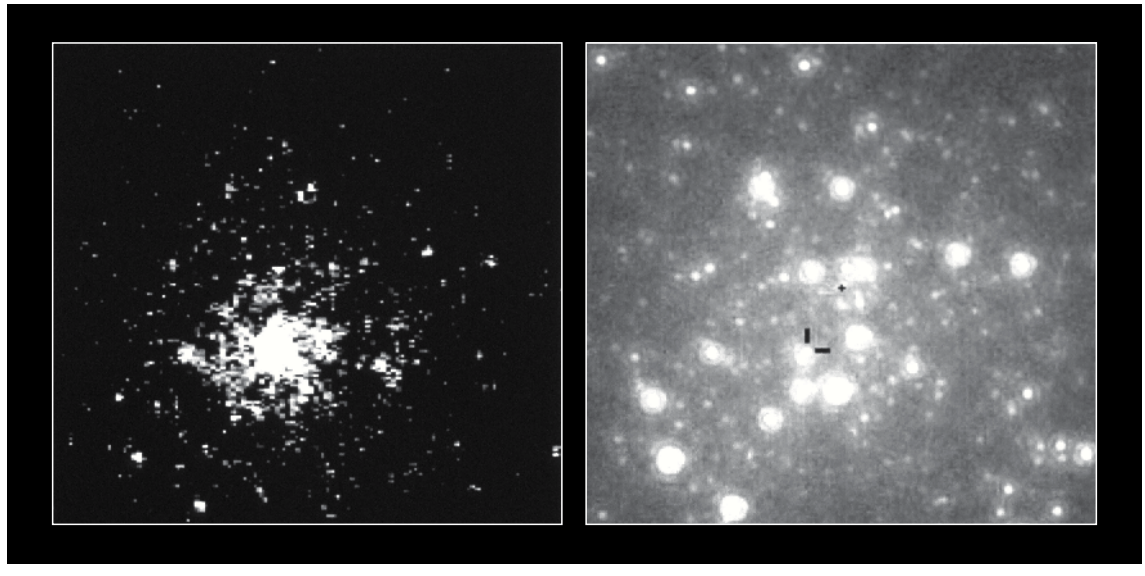


► **WHAT HAPPENS** when stars collide? Astronomers used a Hubble image of globular cluster Omega Centauri (NGC 5139) to help answer that question. When stars collide, they probably merge and make one bigger star. But if the collision is a near miss, they may go into orbit around each other, forming a close binary-star system.

Astronomers found two binary-star systems in this Hubble image. Both of them are close pairs in which one component is a white dwarf that pulls gas off of its companion star.

When the gas falls onto the white dwarf's surface, it heats up and emits ultraviolet light. These unusual emissions enabled scientists to pinpoint these two systems among the myriad faint stars in the cluster.

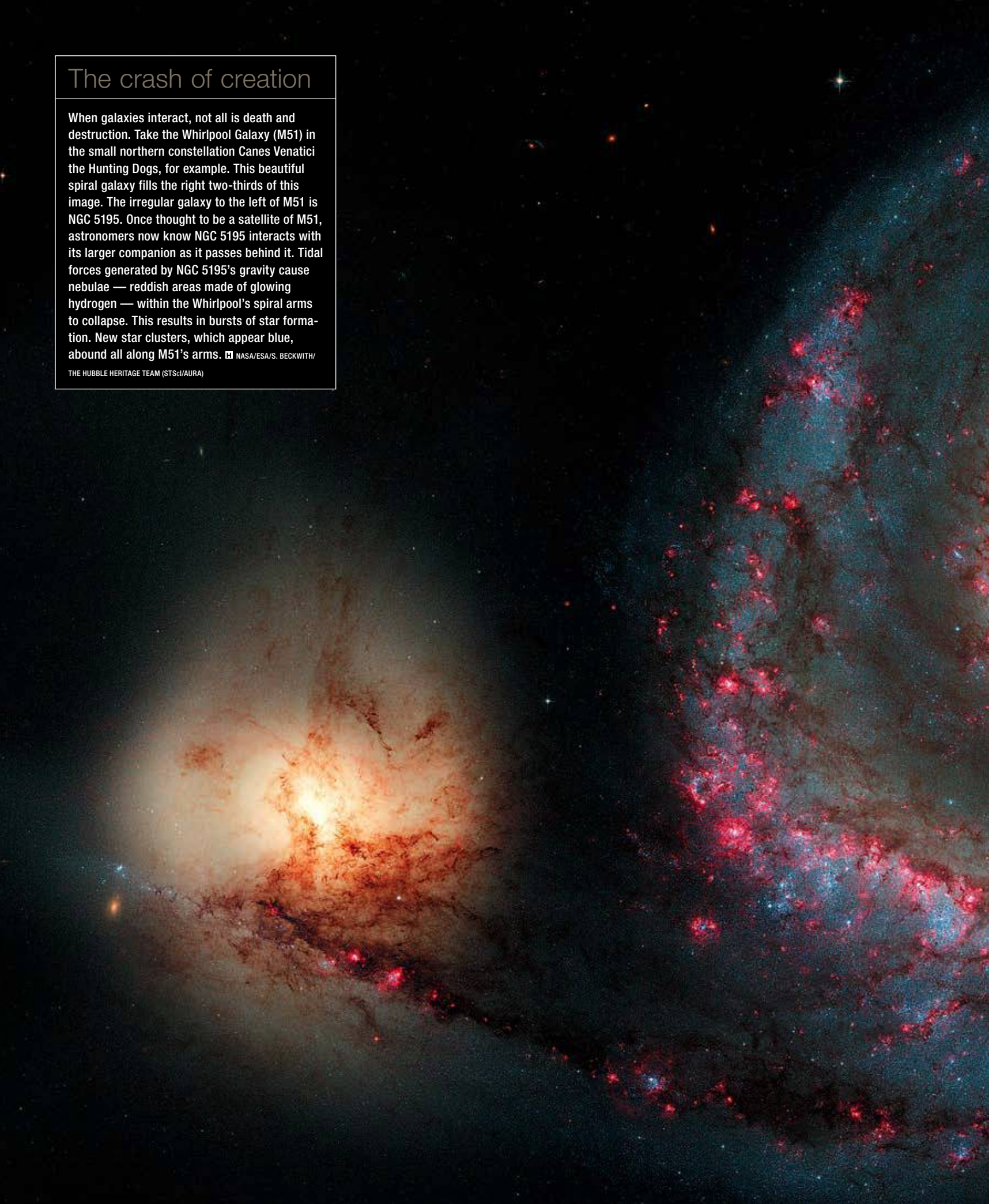
Omega Centauri is so large, only part of it fits within the field of view of Hubble's Wide Field and Planetary Camera 2. Yet even this tiny patch contains some 50,000 stars, all packed into a region only about 13 light-years wide. NASA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



►► **DIFFERENT IMAGES** of globular cluster NGC 6624's core allow astronomers to pick out the faint blue counterpart to an X-ray burster buried in the cluster. An X-ray burster is a double star that emits bursts of X rays.

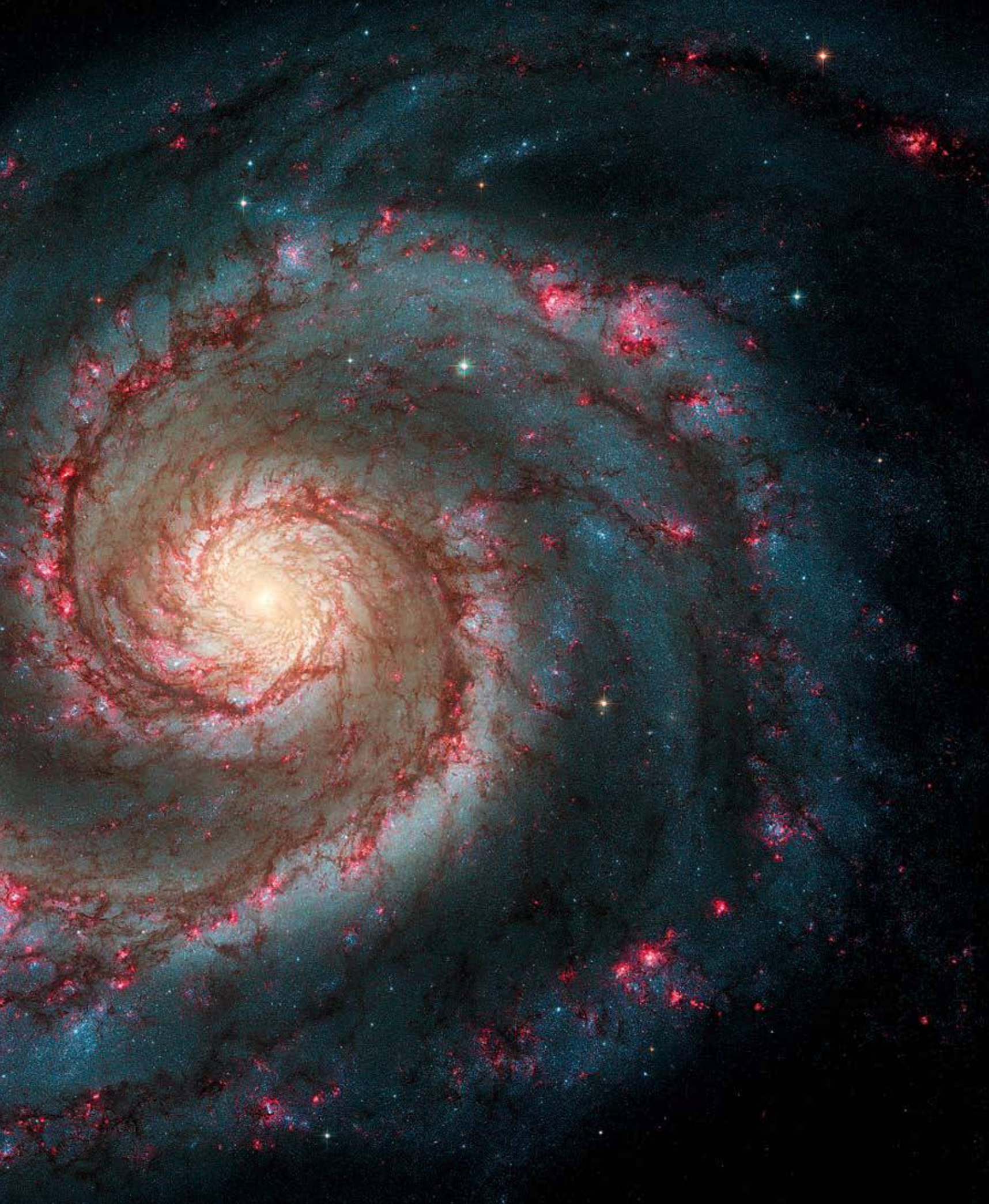
Hubble acquired the left image through an ultraviolet filter and the right image through a visual filter. The mainly red stars look brighter through the visual filter.

Astronomers identified the X-ray source as a neutron star and a white dwarf that orbit each other every 11 minutes. NGC 6624 lies 28,000 light-years away in Sagittarius. IVAN KING (UNIV. OF CALIFORNIA, BERKELEY)/NASA/ESA



The crash of creation

When galaxies interact, not all is death and destruction. Take the Whirlpool Galaxy (M51) in the small northern constellation Canes Venatici the Hunting Dogs, for example. This beautiful spiral galaxy fills the right two-thirds of this image. The irregular galaxy to the left of M51 is NGC 5195. Once thought to be a satellite of M51, astronomers now know NGC 5195 interacts with its larger companion as it passes behind it. Tidal forces generated by NGC 5195's gravity cause nebulae — reddish areas made of glowing hydrogen — within the Whirlpool's spiral arms to collapse. This results in bursts of star formation. New star clusters, which appear blue, abound all along M51's arms. NASA/ESA/S. BECKWITH/THE HUBBLE HERITAGE TEAM (STScI/AURA)



NUTS AND BOLTS

Inside the Hubble

Components labeled in red either have failed or need replacement.

Space Telescope Imaging Spectrograph (STIS)
In 1997, STIS replaced the Goddard High-Resolution Spectrograph. STIS stopped working in late 2004 and may be repaired in 2008.

Primary mirror
This 94-inch (2.4m) mirror is the telescope's main optical element. It's kept at a near-constant temperature of 70° F (21° C).

Advanced Camera for Surveys (ACS)
In 2002, astronauts replaced the Faint Object Camera with ACS. Two of the instrument's three cameras no longer work.

Faint Object Spectrograph
This instrument made spectroscopic observations. In 1997, it was replaced with the Near Infrared Camera and Multi Object Spectrometer (NICMOS).

Gyroscopes (3)
Each unit contains two gyros, for a total of six. Three gyros provide a reference system for pointing Hubble.

Wide Field Planetary Camera 2 (WFPC2)
In 1993, astronauts replaced the Wide Field Planetary Camera with WFPC2. Wide Field Camera 3 will replace it in 2008.

Star trackers (3)
They track bright stars to help establish Hubble's attitude before the scope tries to acquire guide stars needed for observing.

High Speed Photometer
Hubble's "glasses" — the Corrective Optics Space Telescope Axial Replacement, or COSTAR — replaced this instrument in 1993. WFPC2 and all newer instruments correct for the mirror's flaw internally.

Nickel-hydrogen batteries (6)
The batteries store solar power for nighttime operations.

Primary-mirror actuators (24)
These moveable rods make slight changes to the mirror's shape.

Fine Guidance Sensors (3)
They lock onto guide stars to give Hubble a precise positional reference.

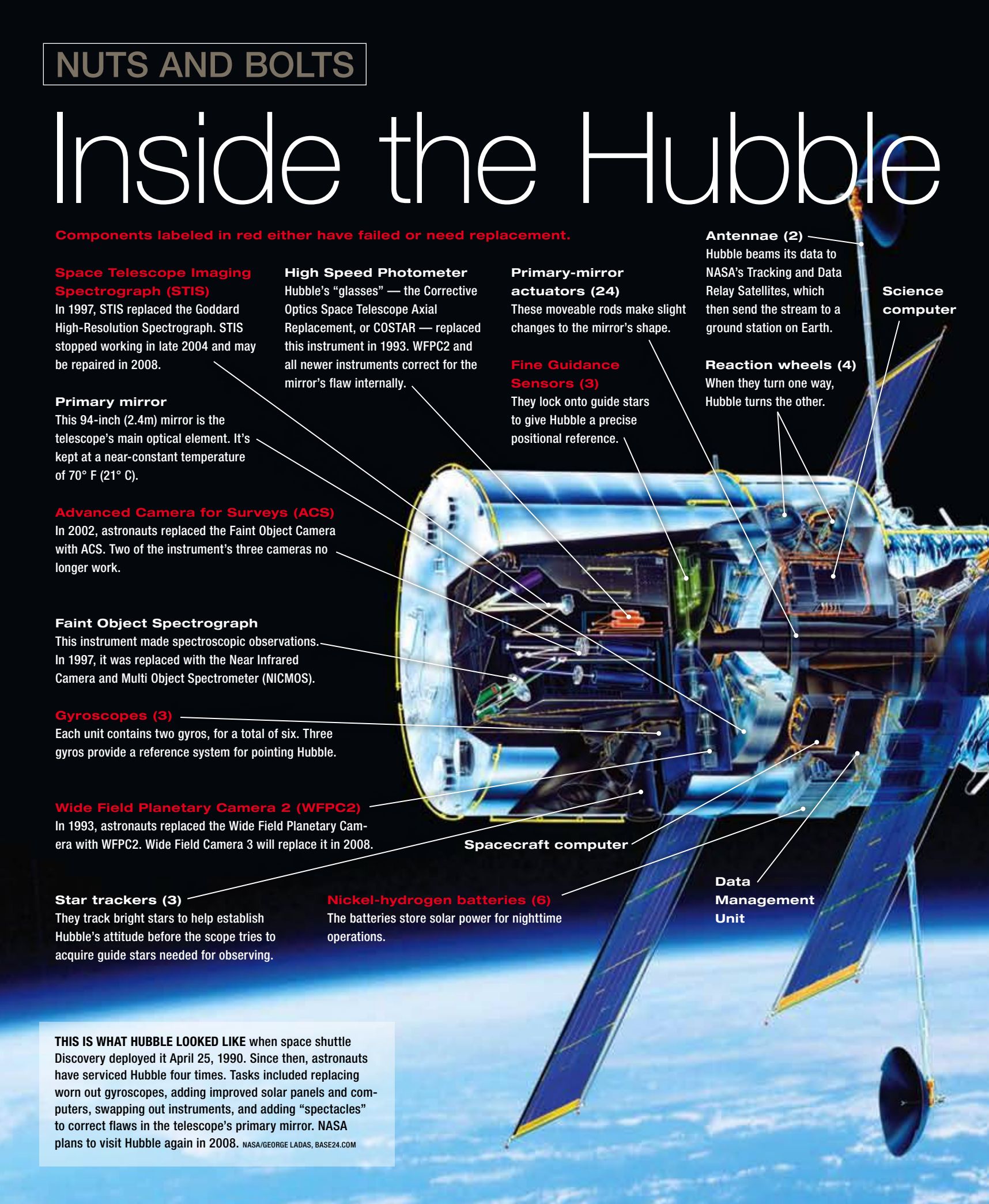
Antennae (2)
Hubble beams its data to NASA's Tracking and Data Relay Satellites, which then send the stream to a ground station on Earth.

Reaction wheels (4)
When they turn one way, Hubble turns the other.

Science computer

Spacecraft computer

Data Management Unit

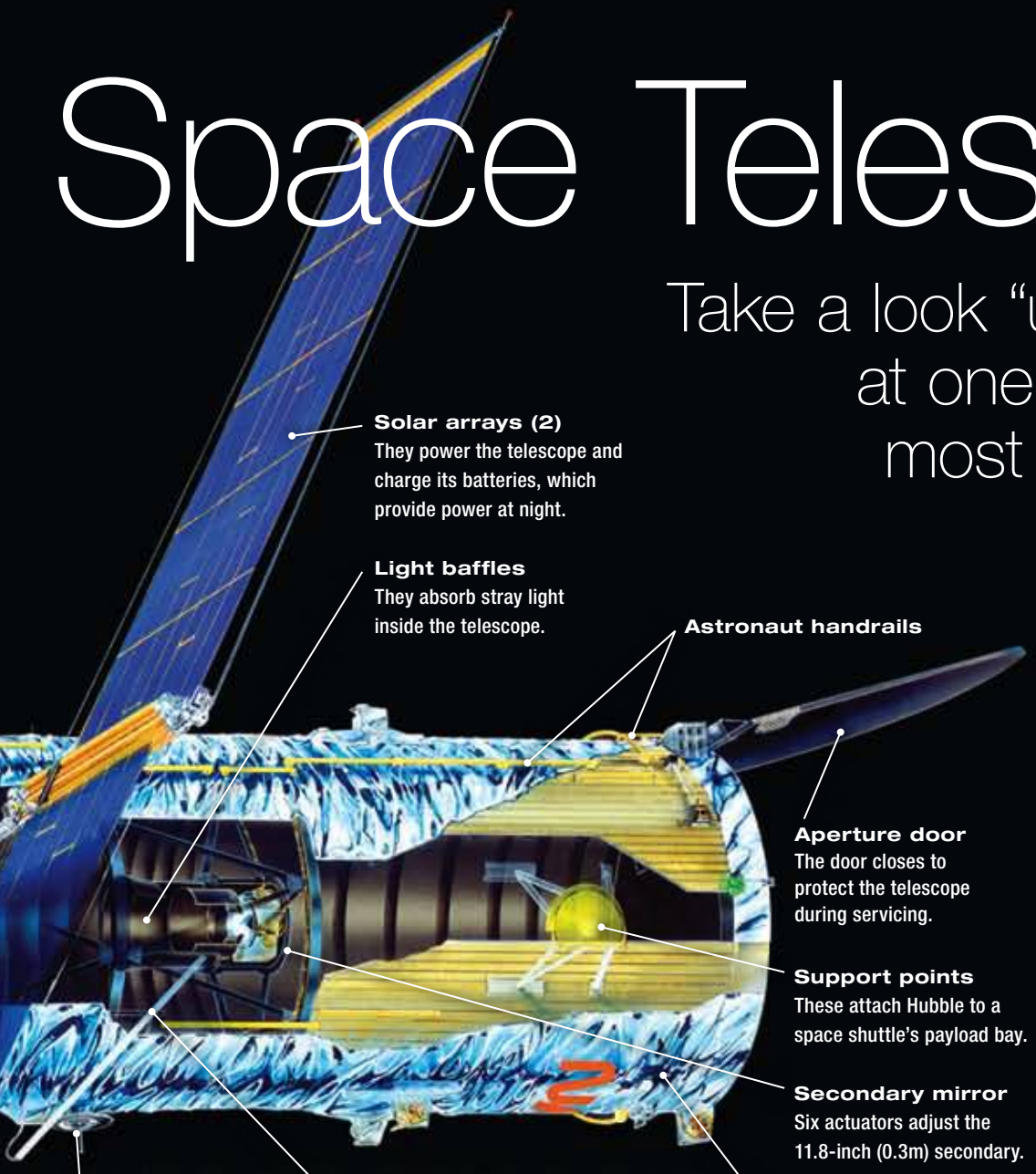


THIS IS WHAT HUBBLE LOOKED LIKE when space shuttle Discovery deployed it April 25, 1990. Since then, astronauts have serviced Hubble four times. Tasks included replacing worn out gyroscopes, adding improved solar panels and computers, swapping out instruments, and adding "spectacles" to correct flaws in the telescope's primary mirror. NASA plans to visit Hubble again in 2008. NASA/GEORGE LADAS, BASE24.COM

Space Telescope

Take a look "under the hood" at one of astronomy's most important tools.

/// BY FRANCIS REDDY



Solar arrays (2)
They power the telescope and charge its batteries, which provide power at night.

Light baffles
They absorb stray light inside the telescope.

Astronaut handrails

Aperture door
The door closes to protect the telescope during servicing.

Support points
These attach Hubble to a space shuttle's payload bay.

Secondary mirror
Six actuators adjust the 11.8-inch (0.3m) secondary.

Attachment fixture
This is what the shuttle's robotic arm holds onto.

Magnetic Torquer Bars (4)
These electromagnets react with Earth's magnetic field to control reaction-wheel speeds.

Insulation
This 16-layer, Teflon-coated blanket helps maintain Hubble's temperature.

Roughly the size of a school bus, the Hubble Space Telescope is one of the most complex, sensitive, and versatile observatories ever built. Hubble is an outstanding success, in part because, during space shuttle visits, astronauts have repaired and improved the telescope's hardware.

On April 25, 1990, the space shuttle Discovery released Hubble into a 366-mile-high (590 kilometers), 96-minute orbit around Earth. But in June, astronomers' worst fears came true — tests revealed a flaw in Hubble's 94-inch (2.4 meters) main mirror. The telescope was effectively near-sighted. In December 1993, shuttle astronauts installed additional optics to correct the flaw. Hubble reached the height of its observing power.

In 1997, 1999, and 2002, shuttle astronauts swapped out instruments and made fresh repairs. But the $1.5 billion telescope needs help again. In late 2008, NASA plans to install new instruments and replace aging and failed components — if the ailing telescope can hold out till then.

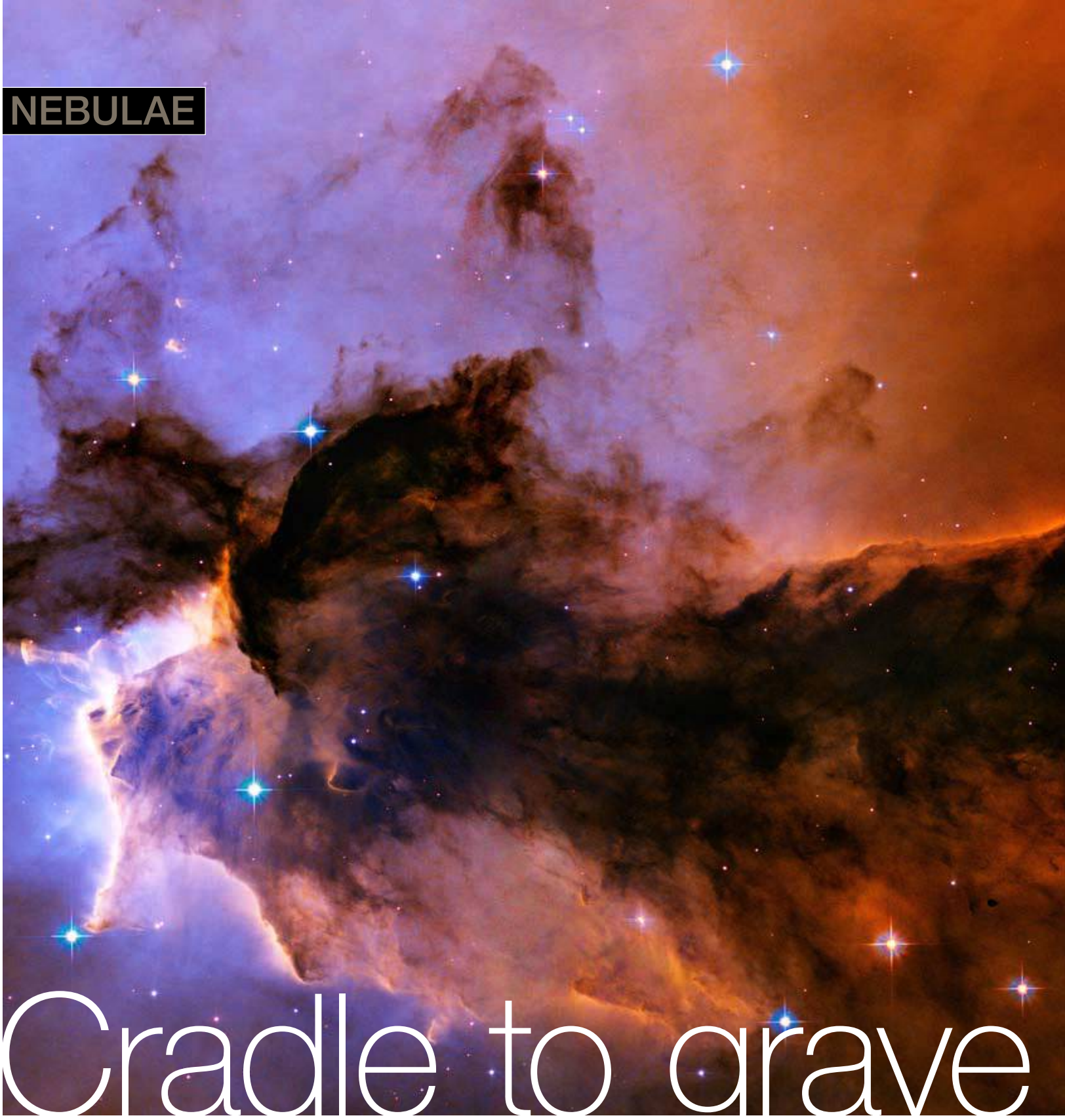
VITAL STATISTICS

Mass: 24,500 pounds (11,110 kilograms)
Length: 43.5 feet (13.2 meters)
Width: 13.8 feet (4.2m)
Optical design: Ritchey-Chrétien
Primary mirror: 94 inches (2.4m)

THE ORBITAL ADVANTAGE

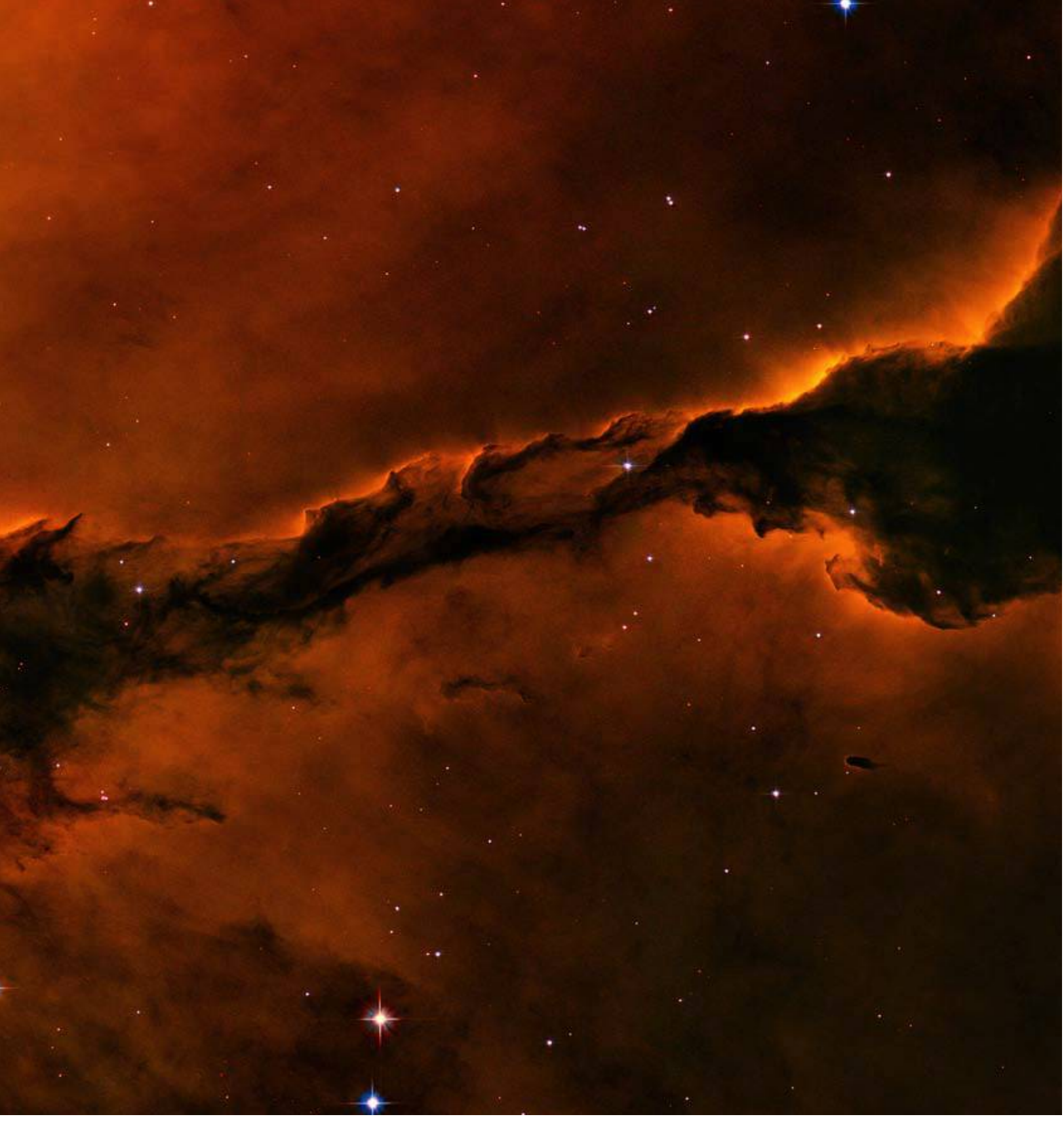
Why put a telescope in orbit? There are three good reasons:

- Turbulence in Earth's atmosphere limits a telescope's angular resolution — its ability to separate two objects that are very close together. Hubble sees 5 times more sharply than a similar-sized ground-based scope.
- Earth's atmosphere screens out many wavelengths — like infrared and ultraviolet light — that tell astronomers a great deal about the cosmos. In space, a telescope can study all wavelengths.
- On Earth, the day-night cycle limits a telescope's working time to at best half a day. A scope in orbit can collect data 24 hours a day.



Cradle to grave

The universe's most beautiful objects show us how stars are born and how they die.



▲ **THIS HUGE TOWER** of cold gas and dust in the Eagle Nebula (M16) measures 9.5 light-years, or about 57 trillion miles (92 trillion km) long, about twice the distance from our Sun to the next nearest star, Alpha Centauri. Stars in the Eagle Nebula are born in clouds of cold hydrogen that reside in chaotic neighborhoods, where energy from young stars sculpts the gas. The tower may be a giant incubator for such newborn stars.

A torrent of ultraviolet light from a group of massive, hot, young stars (which lie to the left, outside the image's field of view) is eroding the pillar. The starlight also illuminates the tower's seemingly rough surface. Ghostly streamers of gas boil off this surface, creating the haze around the structure and highlighting its three-dimensional shape. The background glow of more distant gas silhouettes the column.

Inside the dust and gas tower, stars may be forming, perhaps as gravity collapses regions of cold, dense gas. Other stars may be forming due to pressure from gas heated by radiation emitted from neighboring hot stars. The star birth probably began before the star cluster heated up the area. The bumps and "fingers" of material at the tower's center show star-forming regions. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

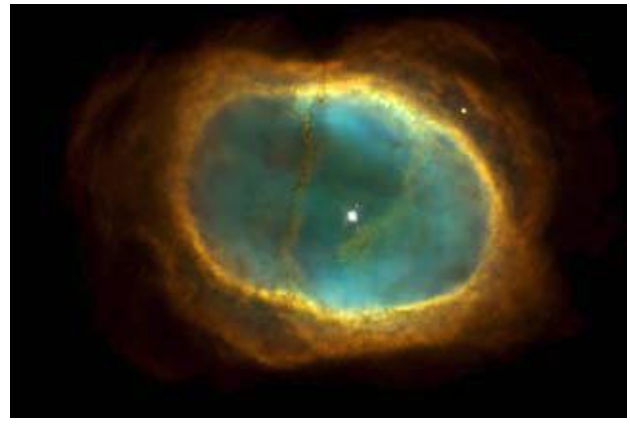
The universe's most beautiful and most colorful objects — the flowers of the cosmos — are nebulae. The word "nebula" comes from Latin for "mist," or "cloud," and, indeed, these objects are vast clouds light-years across composed of gas and dust.

Three types of nebulae inhabit space: emission, reflection, and dark. Another class — planetary nebulae — form when Sun-like stars shed their outer atmospheres at the ends of their lives.

Roses in the dark

Emission nebulae, composed mainly of the simplest element, hydrogen, glow brightly. To do so, however, they require an energetic radiation source. Near all emission nebulae blazes a hot, bright star. Sometimes the star lighting up the nebula formed and lies within the cloud itself. In many cases, an entire star cluster is responsible for the energy created.

In all cases, the star pours ultraviolet (UV) radiation into the nebula's hydrogen atoms. The atoms absorb



◄ THE TARANTULA NEBULA shows a sweeping view of a star-forming region. Hubble's Wide Field and Planetary Camera 2 (WFPC2) took this visible-light image. The brilliant cluster R136, containing dozens of massive stars, lies at the center.

The image reveals several dust pillars that point toward R136, some with bright stars at their tips. The energetic radiation and high-speed material emitted by the massive stars in R136 shape the pillars and cause the heads of some of them to collapse, which forms new stars. NASA/JOHN TRAUGER (JPL)/ JAMES WESTPHAL (CALTECH)

▲ THE EIGHT-BURST NEBULA (NGC 3132), sometimes called the Southern Ring Nebula, is a striking example of a planetary nebula. NGC 3132 lies about 2,000 light-years away in the constellation Vela and is one of the nearest planetary nebulae.

This Hubble image clearly shows two stars near the nebula's center: a bright white one, and a fainter companion to its upper right. The faint partner star that ejected the nebula is now a white dwarf. The flood of ultraviolet radiation from its surface excites the surrounding gases. NASA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

this energy but can hold onto it only for a short time. When they release the energy, however, it's in a different form. Rather than UV radiation, hydrogen reemits the energy as light with a characteristic red glow.

Other elements within the nebula also may absorb UV radiation and reemit the energy as different colors. So, astronomers can get an overall sense of a nebula's chemical composition by looking at the radiation emitted as various colors.

Hubble has imaged hundreds of emission nebulae, including some of the brightest and best-known in the sky. They include the Orion Nebula (M42) in Orion, the Eagle Nebula (M16) in Sagittarius — where Hubble took the famous "Pillars of Creation" image — and the Eta Carinae Nebula (NGC 3372), which lies in the southern constellation Carina the Keel.

Because emission nebulae give off light at specific wavelengths, some manufacturers have produced filters that allow only those wavelengths to pass through. Hubble uses such filters to isolate the most energetic wavelengths coming from nebulae. It's those energy levels that convey the most information.

Amateur astronomers also take advantage of this technology. Using such a filter when observing a nebula through a telescope greatly enhances the view in two ways. First, it increases the contrast between the

— *Continued on page 66*

◄ **THE ORION NEBULA** (M42) contains roiling dust and gas where thousands of stars are forming. This Hubble image reveals more than 3,000 various-sized stars. Some of them had never been seen in visible light.

The Orion Nebula's bright central region — called the Trapezium — is the home of the nebula's four most massive stars. Ultraviolet light from these stars carves a cavity in the nebula and disrupts the growth of hundreds of smaller stars.

Located near the Trapezium are more than 150 stars still young enough to have disks of material around them. Astronomers call these structures protoplanetary disks, or "proplyds," (first discovered by Hubble in 1992). Proplyds are the building blocks of planetary systems.

The bright glow at upper left is from De Mairan's Nebula (M43), a small region astronomers call a miniature Orion Nebula because only one star within it is sculpting the gas there.

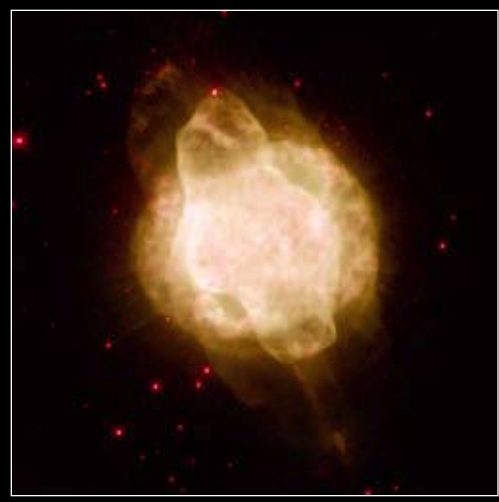
The faint red stars near the bottom of the image are myriad brown dwarfs — cool objects too small to be ordinary stars because they cannot sustain nuclear fusion in their cores.

NASA/ESA/M. ROBBERTO (STScI/ESA)/THE HUBBLE SPACE TELESCOPE ORION TREASURY PROJECT TEAM

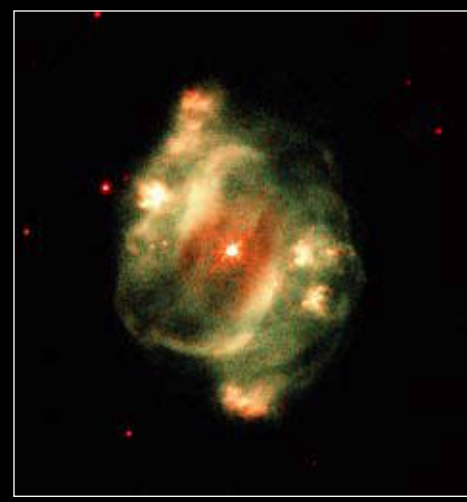
Hubble planetary gallery

▼ **IC 3568** lies in the constellation Camelopardalis at a distance of about 9,000 light-years and measures about 0.4 light-year across. This round planetary nebula has a bright inner shell and a smooth, circular outer envelope. HOWARD BOND (STScI)/ROBIN CIARDULLO (PENNSYLVANIA STATE UNIV.)/NASA

◄ **NGC 6826,** called the Blinking Planetary, has an eye-like appearance marred by two sets of blood-red "fliers" that lie at opposite ends of the nebula. The surrounding green in the eye is gas that once made up almost half of the star's mass. The white dwarf in the center of the green oval drives an energetic wind of particles into older material, forming a hot interior bubble that pushes the older gas ahead of it to form a bright rim. BRUCE BALICK AND JASON ALEXANDER (UNIV. OF WASHINGTON)/ARSEN HAJIAN (USNO)/YERVANT TERZIAN (CORNELL UNIV.)/MARIO PERINOTTO (UNIV. OF FLORENCE, ITALY)/PATRIZIO PATRIARCHI (ARCETRI OBSERVATORY, ITALY)/NASA



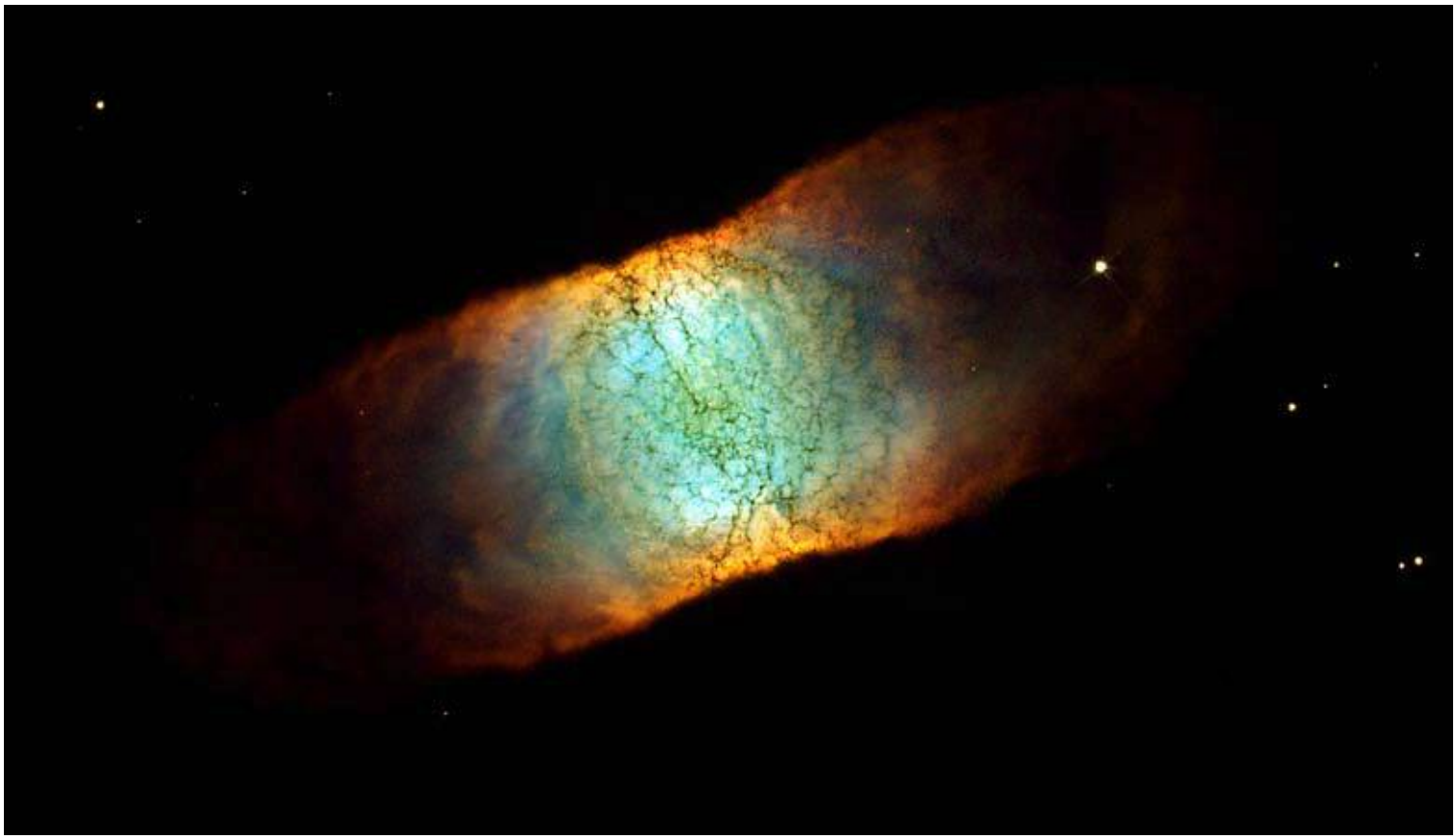
◄ **PLANETARY NEBULA NGC 3918** measures 0.3 light-year across. It lies in the southern constellation Centaurus about 3,000 light-years away. It shows a roughly spherical outer envelope and an elongated inner "balloon" inflated by a fast wind from the hot central star. The balloon is starting to break out of the spherical envelope at the top and bottom. HOWARD BOND (STScI)/ROBIN CIARDULLO (PENNSYLVANIA STATE UNIV.)/NASA



▲ **HUBBLE 5** is a "butterfly," or bipolar (two-lobed), planetary nebula. Heat generated by fast winds causes each of the lobes to expand. Hubble 5 lies 2,200 light-years away in the constellation Sagittarius. BRUCE BALICK (UNIV. OF WASHINGTON)/VINCENT ICKE (LEIDEN UNIV.)/GARRELT MELLEMA (STOCKHOLM UNIV.)/NASA

▲ **THE SATURN NEBULA** (NGC 7009) in Aquarius has a bright central star that lies at the center of a dark cavity bounded by a football-shaped rim of blue and red gas. The cavity and its rim sit inside smoothly distributed greenish material, gas that formerly made up the star's outer layers. A pair of red ansae, or "handles," lies along the nebula's long axis. BRUCE BALICK AND JASON ALEXANDER (UNIV. OF WASHINGTON)/ARSEN HAJIAN (USNO)/YERVANT TERZIAN (CORNELL UNIV.)/MARIO PERINOTTO (UNIV. OF FLORENCE, ITALY)/PATRIZIO PATRIARCHI (ARCETRI OBSERVATORY, ITALY)/NASA

▲ **NGC 5307** lies in Centaurus about 10,000 light-years away and has a diameter of approximately 0.6 light-year. It is an example of a planetary nebula with a pinwheel, or spiral, structure. Each blob of gas ejected from the central star has a counterpart on the star's opposite side. HOWARD BOND (STScI)/ROBIN CIARDULLO (PENNSYLVANIA STATE UNIV.)/NASA



▲ **THE RETINA NEBULA** (IC 4406) exhibits a high degree of symmetry; the left and right halves are nearly mirror images of each other. Gas and dust form a vast donut of material streaming outward from the dying star. From Earth, we view the donut from the side. The donut confines the intense radiation coming from the dying star. Radiation from the central star ionizes gas inside the donut, making it glow.

Light from oxygen atoms is rendered blue in this image; hydrogen is shown as green, and nitrogen as red. One perplexing feature of IC 4406 is the irregular lattice of dark lanes that criss-cross the nebula's center. These lanes are about 160 astronomical units wide (1 astronomical unit is the distance between Earth and the Sun). We see the lanes in silhouette because they have a density of dust and gas 1,000 times higher than the rest of the nebula. NASA/THE HUBBLE HERITAGE TEAM (STScI/AURA)/C. R. O'DELL (VANDERBILT UNIV.)

► **SUPERNOVA REMNANT N 63A** is a violent and chaotic-looking mass of gas and dust. The object is the remains of a massive star that exploded, spewing its gaseous layers out into an already turbulent region. N 63A is a member of N 63, a star-forming region in the Large Magellanic Cloud (LMC).

Visible from the Southern Hemisphere, the LMC is an irregular galaxy lying 170,000 light-years away. Many of this region's stars are massive. Astronomers estimate the progenitor star that produced N 63A was about 50 times more massive than the Sun. Such a massive star has strong stellar winds that can clear away its surroundings. The supernova that formed N 63A exploded inside the cavity of such a bubble. NASA/ESA/HEIC/THE HUBBLE HERITAGE TEAM (STScI/AURA)

▲ THE OMEGA NEBULA (M17) is a hotbed of star formation about 5,500 light-years away in the constellation Sagittarius the Archer. The release of this image in 2003 commemorated the 13th anniversary of Hubble's launch.

This nebula shows a bubbly ocean of glowing hydrogen and small amounts of other elements such as oxygen and sulfur. Ultraviolet radiation from nearby hot stars is carving and heating the surfaces of cold hydrogen clouds. The warmed surfaces glow orange and red as they reemit the radiation.

The intense heat and pressure cause some material to stream away from those surfaces, which created the glowing veil of even hotter greenish gas. Pressure on the waves' tips may trigger new star formation within them.

This Advanced Camera for Surveys image measures roughly 3 light-years across. The colors in the image represent various gases. Red represents sulfur; green, hydrogen; and blue, oxygen.

NASA/ESA/J. HESTER (ARIZONA STATE UNIV.)

▲ THE STINGRAY NEBULA (Hen-1357) is the youngest known planetary nebula. It lies 18,000 light-years away in Ara.

The bright central star sits in the middle of a green ring of gas. Its companion star lies diagonally above it, at 10 o'clock. The curved red lines represent gas heated by a shock caused when the central star's wind interacted with surrounding gas.

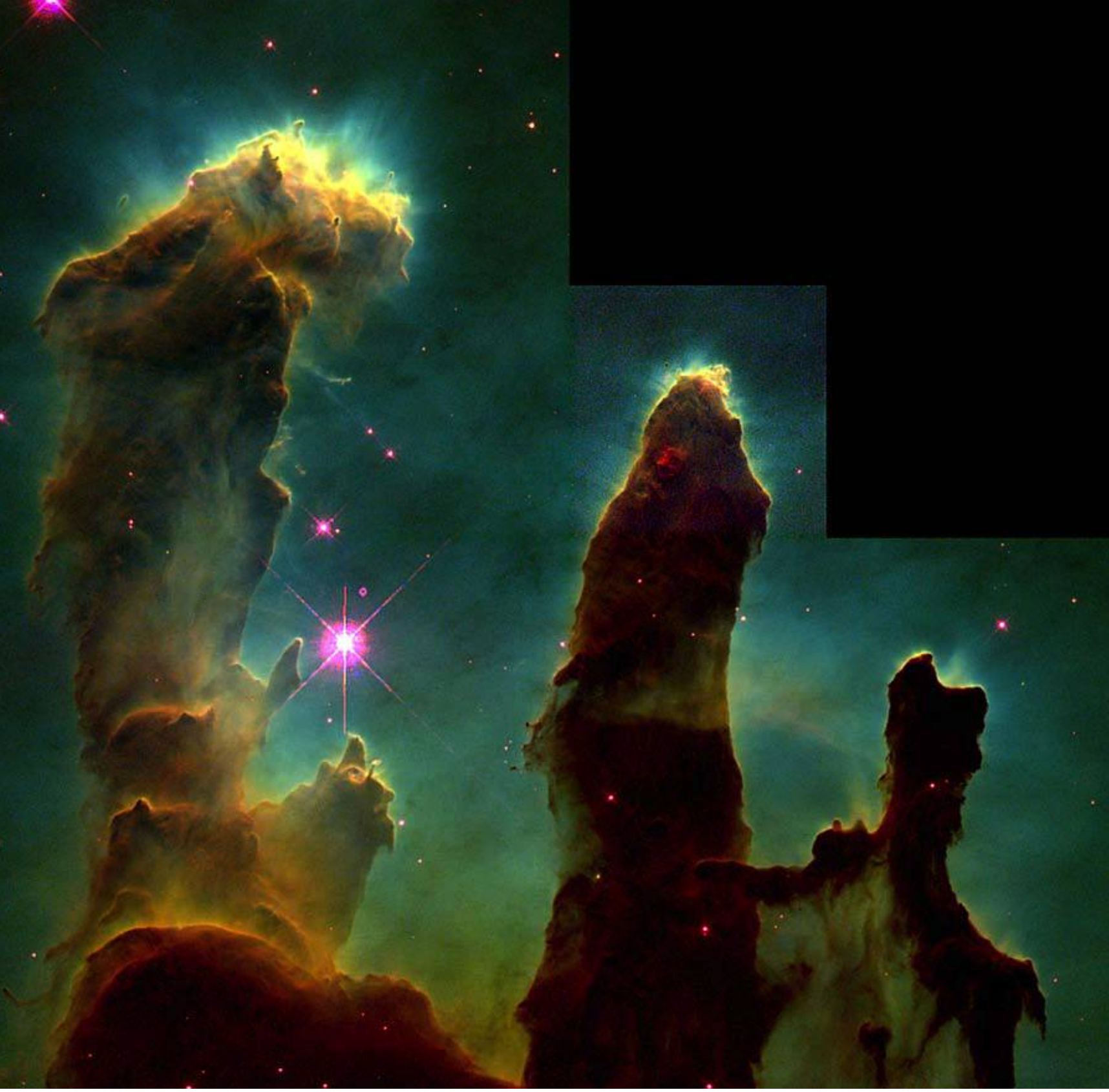
The actual colors shown result from nitrogen (red), oxygen (green), and hydrogen (blue).

NASA/ESA/J. HESTER (ARIZONA STATE UNIV.)

▲ A CLOSE-UP of the Dumbbell Nebula (M27) shows a flurry of glowing knots of gas that appear to be streaking through space. The Dumbbell, a nearby planetary nebula in the northern constellation Vulpecula the Fox, lies approximately 1,200 light-years away. It is the result of an old Sun-like star that has shed its outer layers, producing a glowing display of color.

Hubble revealed many knots of various shapes. Some look like fingers pointing at the central star, which lies just off the upper left of the image; others are isolated clouds, with or without comet-like tails. Their sizes range from 11 to 35 billion miles (17 to 56 billion km). Each knot contains as much mass as 3 Earths.

The knots form at the boundary between the nebula's hot and cool parts. This area of temperature differentiation moves outward from the central star as the nebula evolves. In the Dumbbell, astronomers observe the knots within regions soon after this hot gas has passed by. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



▲ **THE "PILLARS OF CREATION"** lie within the Eagle Nebula (M16) in the constellation Serpens. These features are columns of cool interstellar hydrogen and dust that serve as incubators for new stars. The pillars protrude from the interior wall of a dark molecular cloud like stalagmites from a cavern floor.

Pillars such as these form because dense clouds of molecular hydrogen and dust have survived longer than their surroundings in the face of a flood of ultraviolet radiation from hot, massive newborn stars that lie nearby. This process is called photoevaporation.

The tallest pillar is about 4 light-years long from base to tip — about the same distance between the Sun and the next nearest star, Alpha Centauri. As the pillars slowly erode, small globules of even denser gas buried within the pillars come into view. Astronomers call these globules Evaporating Gaseous Globules (EGGs). Forming inside at least some of the EGGs are embryonic stars. Eventually, the stars emerge as the EGGs succumb to photoevaporation.

Hubble's Wide Field and Planetary Camera 2 took this image April 1, 1995. NASA/ESA/STScI/ J. HESTER AND P. SCOWEN (ARIZONA STATE UNIV.)

— *Continued from page 61*

nebula and any stars around it. Second, it suppresses light pollution, which originates here on Earth. Hubble's light-pollution filter is its location, high above the glow of terrestrial interference.

In a mirror brightly

Reflection nebulae appear mostly blue, but this color isn't due to reemission of energy, as in emission nebulae. Rather, these clouds look blue for the same reason Earth's clear daytime sky appears blue: scattering.

As sunlight passes through our atmosphere, air molecules and microscopic dust grains scatter the light in all directions. Because blue light has the shortest wavelength, it scatters more than any other color. A clear, daytime sky, therefore, appears blue.

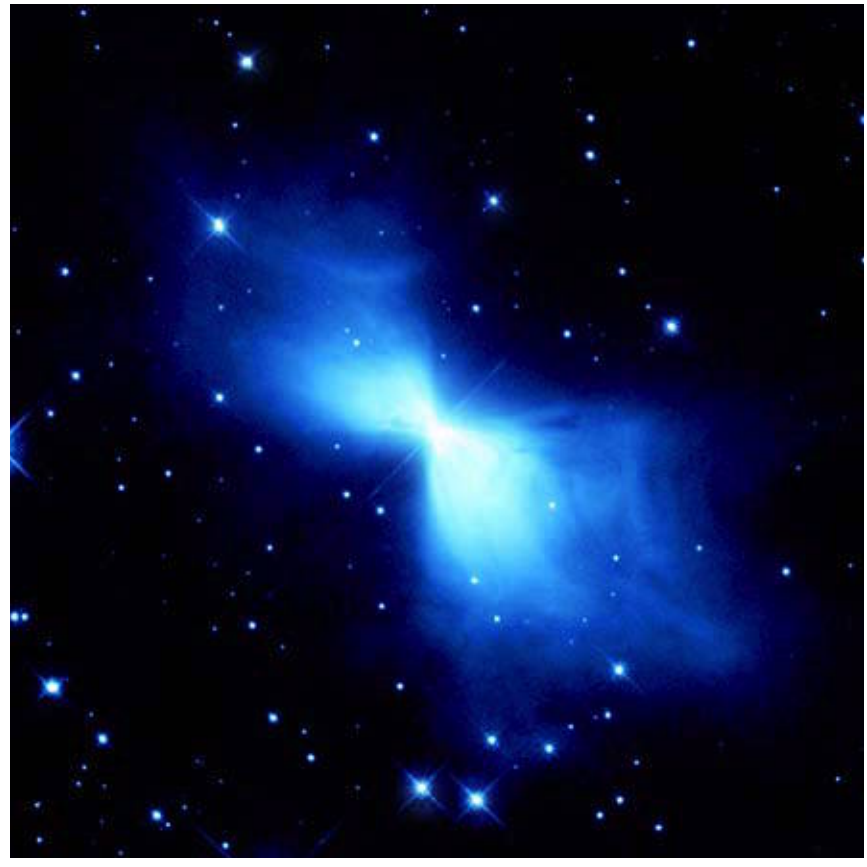
The same process occurs in a reflection nebula. Light from a nearby star strikes the nebula. Unlike with an emission nebula, the star isn't close enough or energetic enough to excite the nebula's atoms. So, the nebulosity simply reflects and scatters the star's light.

While astronomers classify some nebulae as strictly emission and others as only reflection, many nebulae are combinations of the two types. One famous example is the Trifid Nebula (M20) in Sagittarius.

▲ **THE ANT NEBULA** (Menzel 3) resembles a garden-variety ant. This Hubble image, however, shows 10 times more detail than ground-based telescopes and reveals the ant's body as a pair of fiery lobes protruding from a dying Sun-like star.

Hubble images such as this one challenge old ideas about the last stages in the lives of stars. Indeed, our Sun's fate probably will be more interesting, complex, and striking than astronomers imagined just a few years ago.

The Ant Nebula lies in the constellation Norma approximately 3,000 light-years away. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



► **THE BOOMERANG NEBULA** (ESO 172–7) is a reflecting cloud of dust and gas with two nearly symmetric lobes of matter being ejected from a central star. Hubble resolved patterns in the nebula not visible in ground-based images. A visible-light filter in combination with polarizing filters reduced the glare.

The telescope's polarizing filters allow only light of a specific angle to pass through. By combining images taken at different angles, astronomers studied light scattering in the nebula and the properties of the dust responsible for the scattering. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

► **THE CONE NEBULA** (NGC 2264) is a craggy looking mountain of dust and cold gas. This celestial object resembles the Pillars of Creation within the Eagle Nebula (see page 65).

This Advanced Camera for Surveys (ACS) image shows the upper 2.5 light-years of the 7-light-year-long nebula. Radiation from hot, newly formed stars near the top of the pillar sculpts the dust and gas into this shape.

This image was one of the first astronomers released after astronauts aboard space shuttle Columbia (STS-109) installed the ACS during servicing mission 3B in March 2002. The ACS is a 16-megapixel camera.

The Cone Nebula lies in the constellation Monoceros the Unicorn approximately 2,500 light-years away. NASA/H. FORD (JOHNS HOPKINS UNIV.)/G. ILLINGWORTH (UCSC/LO)/M. CLAMPIN AND G. HARTIG (STScI)/THE ACS SCIENCE TEAM/ESA

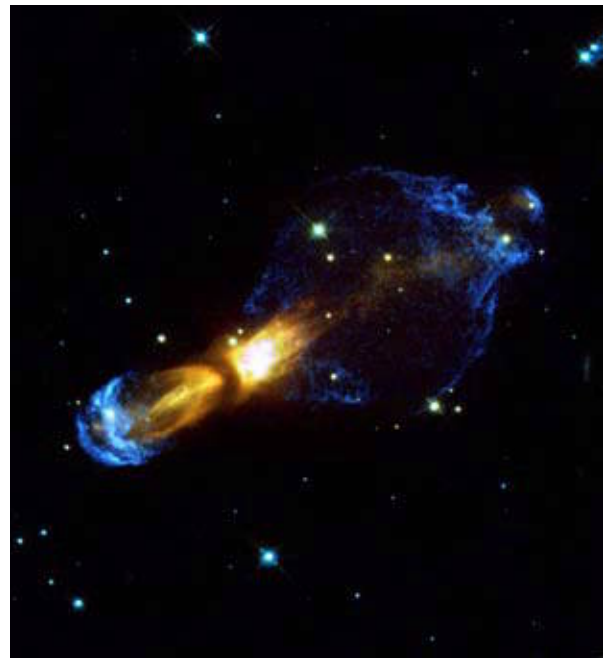
Hide and seek

Astronomers call non-glowing clouds of dust and cold gas dark nebulae. Dark nebulae, as seen from our perspective on Earth, block the light from brighter objects behind them.

From a dark site, you can see many large dark nebulae superimposed on the Milky Way's brighter background. Their forms are irregular, with no well-defined boundaries. Famous examples of dark nebulae include the Coal Sack in the southern constellation Crux and the Horsehead Nebula in Orion.

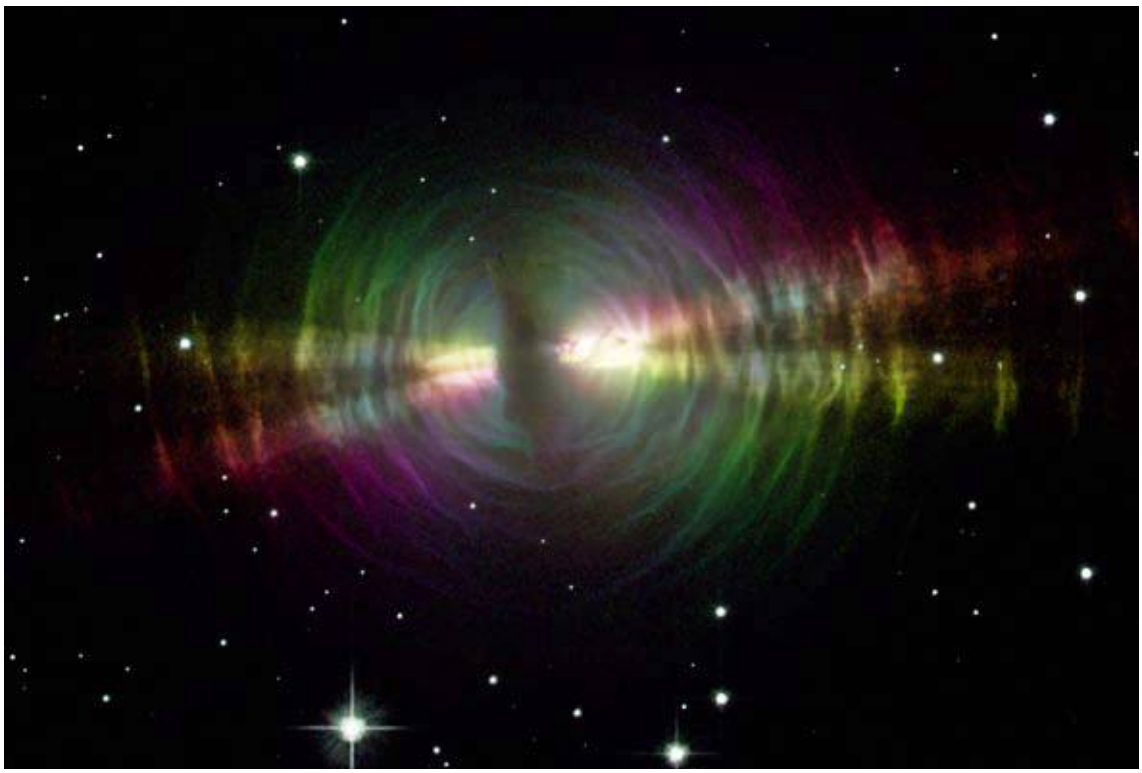
The largest dark nebulae are giant molecular clouds, a type of object whose size and density favors the formation of hydrogen and other molecules. Molecular clouds — some of the coldest regions in space — eventually will collapse under their own gravity and form stars.

Not all dark objects are huge molecular clouds, however. Astronomers call small, isolated dark nebulae Bok globules, after Dutch-American astronomer Bart J. Bok (1906–1983), who was the first to identify them. Dark Bok globules within an emission nebula stand out against the brilliance of the nebula's glowing gas. Bok globules contain up to a dozen times the Sun's mass and commonly form double- or multiple-star systems. H



▲ THIS COSMIC JELLYFISH actually is planetary nebula OH231.8+4.2. Sometimes called the Rotten Egg Nebula, this object is helping to create a protoplanetary nebula. A dying star (hidden behind dust and gas in the center) has ejected massive amounts of gas. Parts of the gas have reached tremendous velocities — up to 900,000 mph (1.5 million km/h).

Shown in blue is light from hydrogen and ionized nitrogen arising from supersonic shocks where the gas stream collides with surrounding material. The image showed, for the first time, these complex gas structures predicted by theory. The Hubble image combines four WFPC2 images taken through four different filters. ESA/VALENTIN BUJARRABAL (OBSERVATORIO ASTRONOMICO NACIONAL, SPAIN)

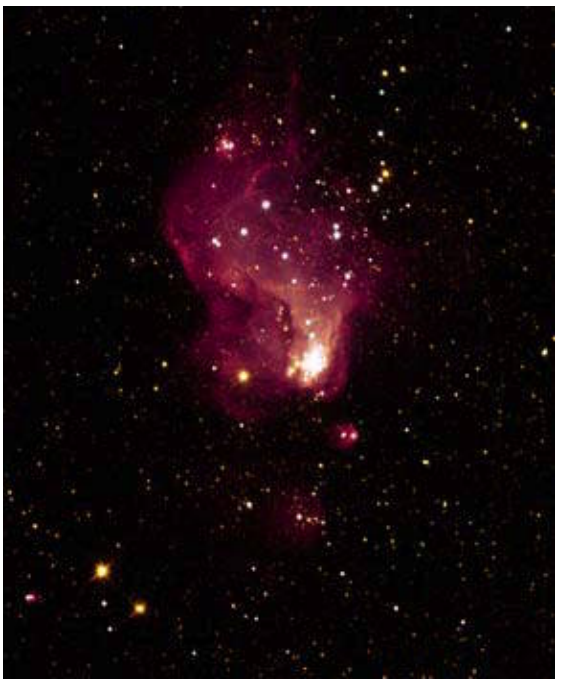


▲ THE EGG NEBULA (CRL2688), located about 3,000 light-years away in the northern constellation Cygnus the Swan, looks like underwater lights. This Hubble image reveals the normally invisible dust shells swaddling an aging star. These dust layers form concentric spheres (which we see as rings) around the star.

Hubble's Advanced Camera for Surveys took several images through polarizing filters. Astronomers then applied artificial colors to each filter's image to show how light reflects off the smoke-sized particles. The light from one of the polarizing filters has been colored red and admits light only from about one-third of the nebula.

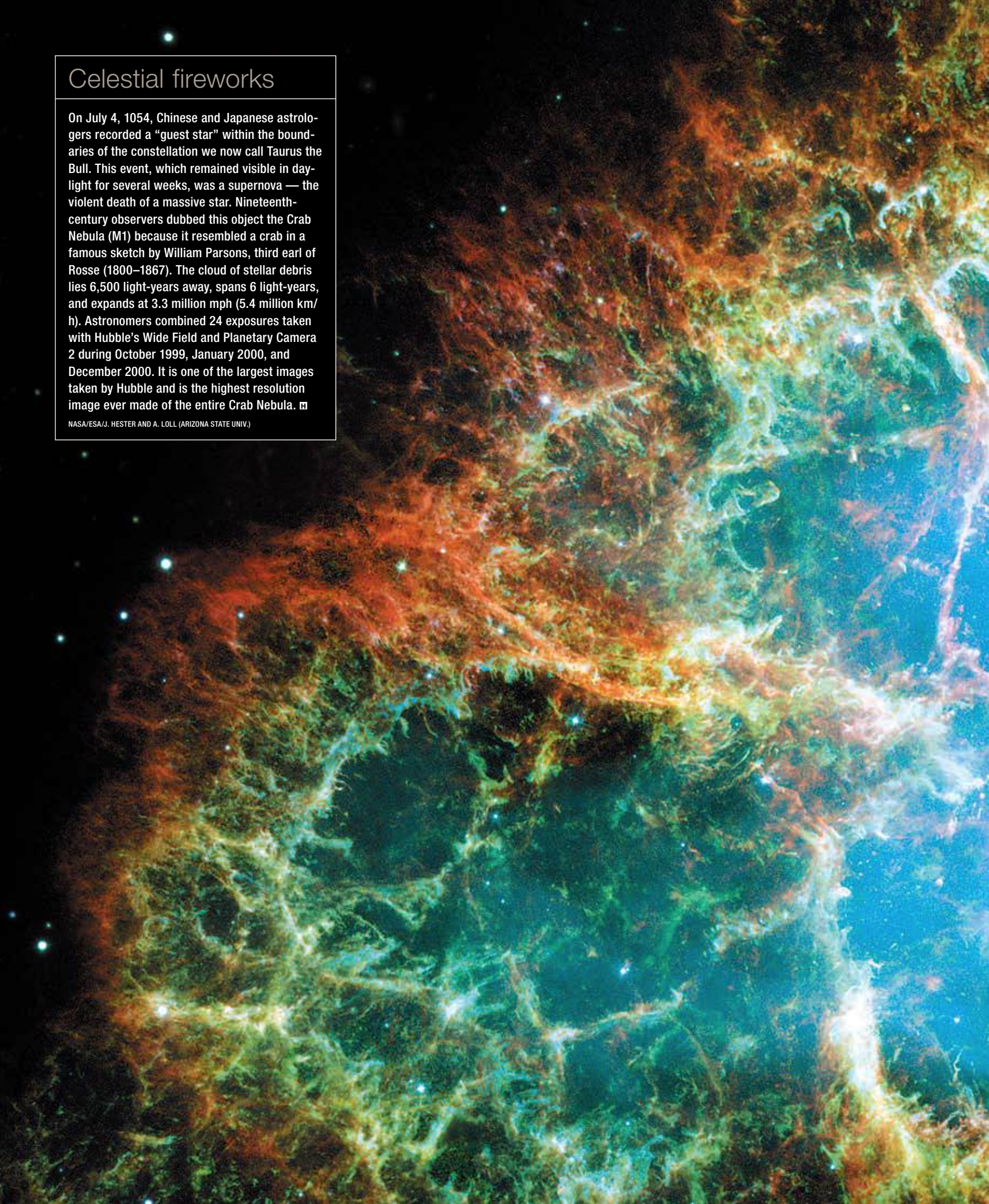
A blue polarizing filter accepts light reflected from a different swath of the nebula. The green comes from the final third of the nebula. Some inner regions appear white because the dust is thicker, and the light is scattered many times in random directions before reaching us. NASA/THE HUBBLE HERITAGE TEAM (STSCI/AURA)/W. SPARKS (STSCI)/R. SAHAI (JPL)

▲ **THE HORSEHEAD NEBULA** (B33) in Orion is the sky's most famous dark nebula. This detailed view celebrated Hubble's 11th anniversary in 2001. The Horsehead is a dark cloud of dust and cold gas silhouetted against the bright nebula IC 434. The bright area at the top left edge of the horse's head is a young star still embedded in its nursery. In a short time, the star will be visible because its energy is eroding the gas and dust surrounding it. NASA/NOAO/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



◄ **HUBBLE-V** is the name astronomers gave to this 200-light-year-wide nebula in Barnard's Galaxy (NGC 6822), which lies 1.6 million light-years away in the constellation Sagittarius. Resembling curling flames from a campfire, this nebula is giving astronomers new insight into star birth in the early universe.

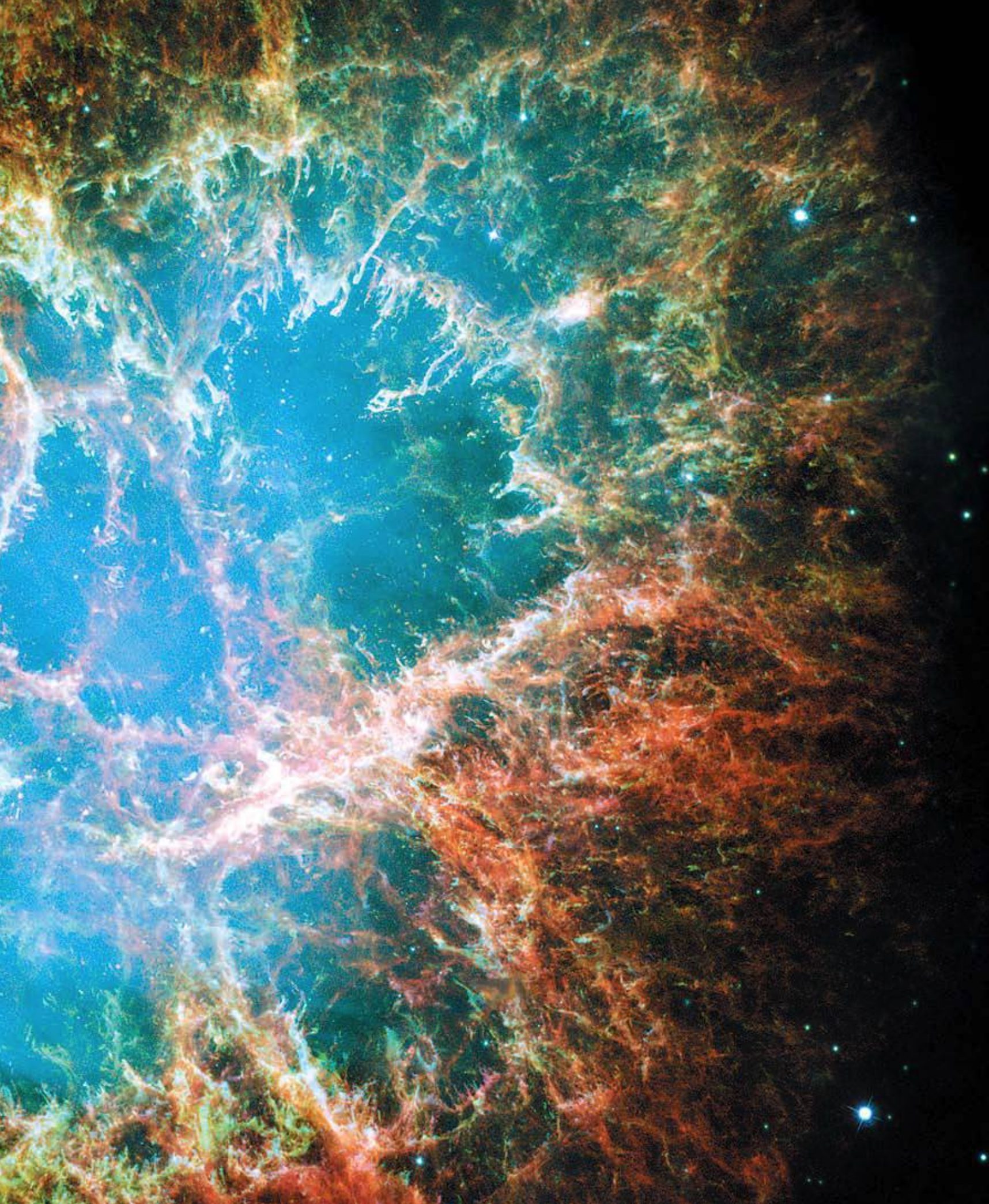
A faint tail of nebulosity trailing off the top of the image sits opposite a dense cluster of bright stars at the bottom of the irregularly shaped nebula. Hubble's resolution and ultraviolet sensitivity revealed a dense knot of dozens of ultrahot stars, each glowing 100,000 times brighter than our Sun. The stars are also young — approximately 4 million years old. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



Celestial fireworks

On July 4, 1054, Chinese and Japanese astrologers recorded a "guest star" within the boundaries of the constellation we now call Taurus the Bull. This event, which remained visible in daylight for several weeks, was a supernova — the violent death of a massive star. Nineteenth-century observers dubbed this object the Crab Nebula (M1) because it resembled a crab in a famous sketch by William Parsons, third earl of Rosse (1800–1867). The cloud of stellar debris lies 6,500 light-years away, spans 6 light-years, and expands at 3.3 million mph (5.4 million km/h). Astronomers combined 24 exposures taken with Hubble's Wide Field and Planetary Camera 2 during October 1999, January 2000, and December 2000. It is one of the largest images taken by Hubble and is the highest resolution image ever made of the entire Crab Nebula. H

NASA/ESA/J. HESTER AND A. LOLL (ARIZONA STATE UNIV.)



Cities of the uni

Hubble's observations help unravel how galaxies form, evolve, move through space, and collide.

verse

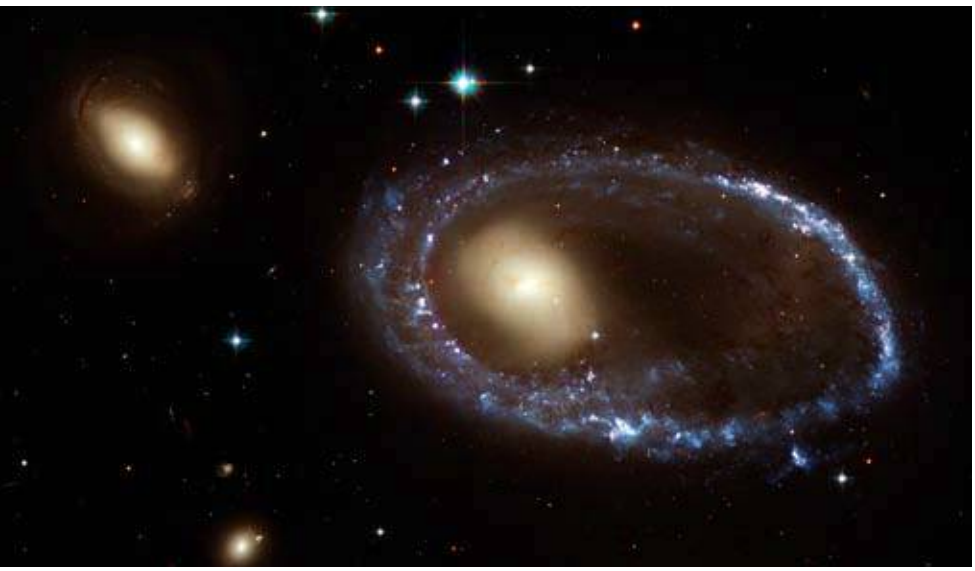
COLLIDING GALAXIES known as the Mice (NGC 4676A and NGC 4676B) lie 300 million light-years away in the constellation Coma Berenices. Astronomers calculated the Mice had their closest encounter 160 million years ago.

In the galaxy on the left, the bright blue patch is a vast region of star formation triggered by the tidal forces of the interaction. The long, straight "tail" of the galaxy on the right actually curves, but we see it edge-on. Faint regions of material separate clumps of young stars within the tail. This suggests the clumps formed from the gravitational collapse of the gas and dust that once occupied those areas. NASA/H. FORD (JHU)/G. ILLINGWORTH (UCSC/LO)/M. CLAMPIN (STScI)/THE ACS SCIENCE TEAM/ESA

Of all the objects Hubble has imaged, galaxies are the most stunning. They represent cities of stars — huge collections of up to a trillion or more individual suns molded by gravity into elegant forms. Each galaxy belongs to a larger cluster or supercluster. Galaxy superclusters are the universe's building blocks — the largest gravitationally bound collections of matter in space.

While Hubble has orbited Earth since April 1990, it has taken thousands of images of galaxies. From the smallest dwarfs to the largest giant ellipticals and the biggest superclusters, each image provides astronomers with more information about galactic motion, dynamics, and evolution. Hubble also has reached back farther in time than any optical telescope before it.

On March 9, 2004, the Space Telescope Science Institute released the Hubble Ultra Deep Field (HUDF) — the space telescope's crowning achievement. The HUDF is the deepest portrait of the universe ever taken. This million-second-long exposure (see page 94) shows the first galaxies to emerge from the so-called Dark Ages, the time shortly after the Big Bang when the first stars reheated the cold, dark universe.



▲ **A BRILLIANT RING** of blue star clusters wraps around the yellowish nucleus of what was once a normal spiral galaxy. The ring measures 150,000 light-years in diameter, making it larger than the Milky Way.

The galaxy, cataloged as AM 0644–741, is a member of the class of so-called ring galaxies. It lies 300 million light-years away in the constellation Volans.

Ring galaxies show how collisions between galaxies can change their structure and trigger star formation. They arise when one galaxy plunges directly through the disk of another. In this case, the galaxy that pierced the ring galaxy lies out of the image. The spiral galaxy visible to the left of the ring galaxy lies in the background.

The gravitational shock from the collision drastically changed the orbits of stars and gas in the galaxy's disk, causing them to rush outward. As the ring plows outward, gas clouds collide, compress, collapse, and form an abundance of new stars.

The release of this Advanced Camera for Surveys image in 2004 commemorated the 14th anniversary of Hubble's launch.

NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

► **WITHIN THE CONSTELLATION** Leo the Lion, the majestic dusty spiral galaxy NGC 3370 looms. Behind it lies a backdrop of far-off galaxies of all types. Hubble observations show intricate spiral-arm structure spotted with hot areas of star formation.

Astronomers measured Cepheid variable stars — stars whose brightness and period of variability are related — to obtain an accurate distance to NGC 3370 of 98 million light-years. Hubble acquired this image in 2003, accumulating 25 hours of exposure time. NASA/THE HUBBLE HERITAGE TEAM/A. REISS (STScI)

Galaxy types

In the 1920s, Edwin Hubble, working at California's Mount Wilson Observatory, created a classification system he applied to galaxies. It forms the basis of the one astronomers use today.

Hubble established three main galaxy classes. Ellipticals represent the largest group. They contain old stars and little interstellar dust and gas. They come in varying degrees of apparent roundness, represented by the numbers 0 through 7. An elliptical designated E0 appears spherical, an E1 is stretched slightly, and an E7 looks like a lens.

Both the largest and smallest galaxies are elliptical galaxies. Giant ellipticals are rare, bloated hulks surrounded by hundreds of globular clusters that rule their regions of space, while dwarf ellipticals are the most common in the universe. Most dwarf ellipticals revolve around larger galaxies.

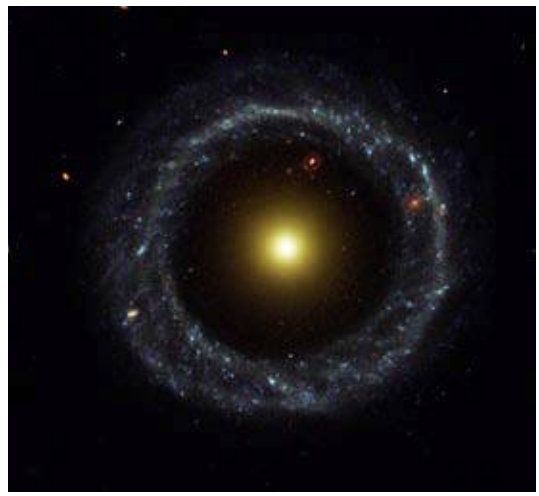
◄ **THE ANTENNAE** (NGC 4038 and NGC 4039) are a magnificent example of colliding galaxies. They lie approximately 65 million light-years away in the constellation Corvus the Crow. As the two galaxies smash together, billions of stars form, mostly in groups and super star clusters. The two spiral galaxies started to fuse about 500 million years ago. That makes the Antennae the nearest and youngest example of a colliding galaxy pair.

The orange blobs are the cores of the two original galaxies and consist mainly of old stars and filaments of dark, brown dust. Brilliant blue star-forming regions surrounded by pink hydrogen dot the two galaxies.

Hubble has helped astronomers better distinguish between the stars and the clusters created in the collision. The Antennae take their name from the long antenna-like "arms" extending far out from their nuclei. NASA/ESA/B. WHITMORE (STScI)/JAMES LONG (ESA/HUBBLE)

▲ **PECULIAR GALAXY** Arp 220 cradles a collision in its heart. The collision has provided the spark for a burst of star formation. The bright, crescent-shaped object is a remnant core of one of the galaxies. A dusty disk about 300 light-years across may obscure its bottom half.

The other galaxy's core is the bright round object to the left of the crescent-shaped object. Arp 220, located 250 million light-years away, lies in the constellation Serpens. RODGER THOMPSON, MARCIA RIEKE, AND GLENN SCHNEIDER (UNIV. OF ARIZONA)/NICK SCOVILLE (CALTECH)/NASA



▲ **HOAG'S OBJECT** lies 600 million light-years away in the constellation Serpens. A nearly perfect ring of hot, blue stars pinwheels about its yellow nucleus. The galaxy spans about 120,000 light-years — slightly larger than our Milky Way. Clusters of young, massive stars dominate the blue ring. Its color contrasts sharply with that of the nucleus, which contains mostly older stars.

Ring-shaped galaxies form in several ways. A collision, where one galaxy speeds through another, is one possibility. But Hoag's Object shows no sign of a second galaxy. The ring may be the shredded remains of a galaxy that passed nearby 2 to 3 billion years ago. NASA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

▲ **ESO 510–G13** in the constellation Hydra the Water Snake is an unusual galaxy seen edge-on. Its warped, dusty disk contrasts with normal spirals like the Milky Way, which appear flat when viewed edge-on. The strong warping of the disk indicates ESO 510–G13 has undergone a recent collision with a nearby galaxy and is in the process of swallowing it.

Gravitational forces distort galaxies as their stars, gas, and dust merge in a process that takes millions of years. Eventually, the disturbances will die out, and ESO 510–G13 will become a normal-looking single galaxy. ESO 510–G13 lies roughly 150 million light-years from Earth.

During observations of ESO 510–G13 April 6/7, 2001, Hubble's Wide Field and Planetary Camera 2 passed the 100,000-image milestone since its installation in 1993. NASA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

▲ **THE CIRCINUS GALAXY** lies 13 million light-years away in the southern constellation Circinus. Astronomers designate this galaxy a type 2 Seyfert, a class of mostly spiral galaxies that have compact centers and contain supermassive black holes.

Seyfert galaxies are part of a larger class of objects called Active Galactic Nuclei, or AGN. AGN remove gas from their host galaxies' centers by blowing it out into space at phenomenal speeds. NASA/ANDREW S. WILSON (UNIV. OF MARYLAND)/PATRICK L. SHOPBELL (CALTECH)/CHRIS SIMPSON (SUBARU TELESCOPE)/THAISA STORCHI-BERGMANN AND F. K. B. BARBOSA (UFRGS, BRAZIL)/MARTIN J. WARD (UNIV. OF LEICESTER)

Although the Hubble Space Telescope has imaged some active ellipticals, elliptical galaxies tend to be featureless and don't make pretty pictures. Most of the fabulous looking galaxy images Hubble has created are of spiral galaxies.

Spirals form the next largest galaxy group, roughly one-quarter of all galaxies in space. They break down into regular and barred types. Regular spirals have a spherical nucleus from which the arms originate. Barred spiral galaxies contain a central bar. The main arms begin from the ends of the bar.

All spiral galaxies have a central bulge. This region contains most of the galaxy's stars. The stars within the central bulge are old and contain only a small percentage of metals (elements other than hydrogen and helium). Younger stars and star-forming regions make up the galaxies' spiral arms. These second-generation (and later) stars contain slightly higher percentages of metals synthesized in supernova blasts.

Irregulars make up the third main galaxy type. Originally, the irregular group was a "catchall" that contained all galaxies not classified as normal ellipticals or spirals. Recently, some small galaxy groups have been isolated from the irregular classification. They include peculiar galaxies (the vast majority of which are distorted by gravitational interactions with other galaxies), starburst galaxies (that form stars at an accelerated rate), and galaxies with active nuclei. Such objects emit more energy than astronomers can account for by the stars in them. Some irregular galaxies show spiral structure, but are distorted.

▲ **NGC 4414** classifies as a flocculent spiral galaxy. Astronomers add the word "flocculent" to indicate this galaxy has a fluffy appearance and that it lacks well-defined spiral arms. The softer appearance of a flocculent spiral's arms probably arises from numerous HII regions (a cloud of glowing gas where star formation occurs) and star clusters containing hot supergiants. NGC 4414 lies 62 million light-years away in the constellation Coma Berenices. NASA/ESA/THE HUBBLE HERITAGE TEAM (AURA/STScI)

▲ **A STAR-FORMING REGION** viewed at multiple wavelengths gives astronomers a better idea of the processes occurring within barred spiral galaxy NGC 1512, which lies in the southern constellation Horologium. Astronomers created this color-composite from seven images taken with three different Hubble cameras: the Faint Object Camera, the Wide Field and Planetary Camera 2, and the Near Infrared Camera and Multi-Object Spectrometer.

The galaxy's core contains a 2,400-light-year-wide circle of infant star clusters, called a "circumnuclear" starburst ring. Starbursts are episodes of vigorous star formation and exist in a variety of galaxy environments. NASA/ESA/D. MAOZ (TEL-AVIV UNIV. AND COLUMBIA UNIV.)

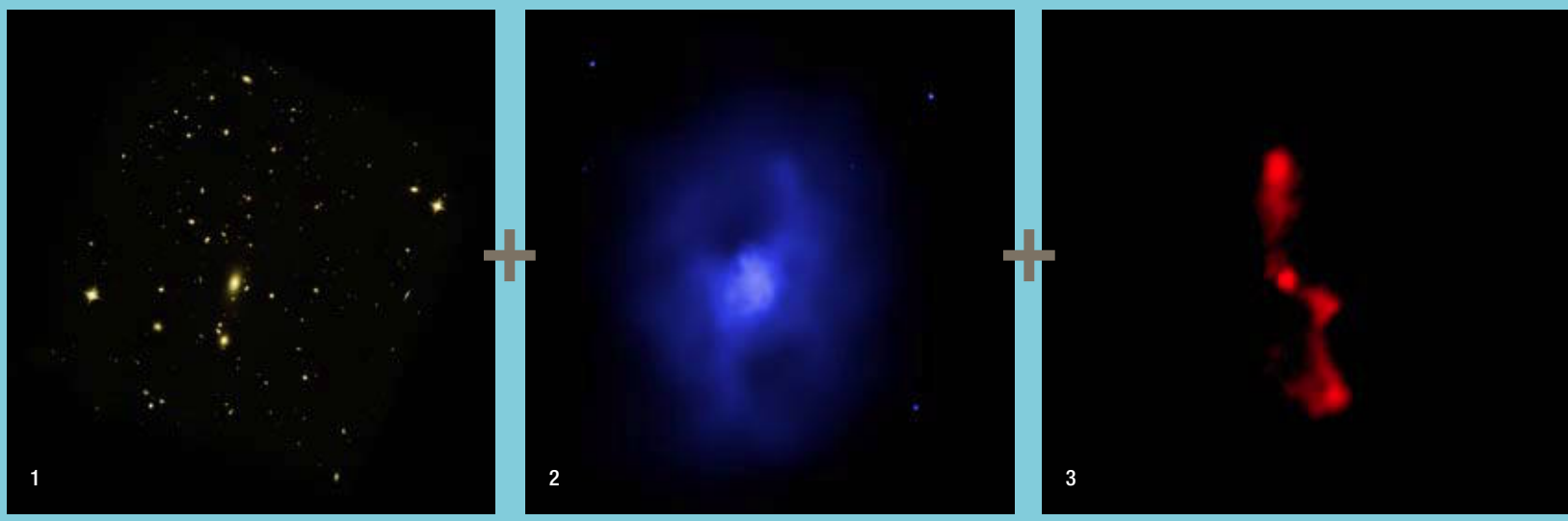
► **LENTICULAR GALAXY** M102 appears tilted edge-on to our line of sight. It contains a flat stellar disk and a large ellipsoidal bulge.

M102 lies in the constellation Draco about 44 million light-years away. The galaxy has a diameter of roughly 60,000 light-years.

Hubble's sharp vision reveals a crisp dust lane dividing the galaxy. A faint red bulge surrounds M102's bright nucleus, and a blue disk of newborn stars runs parallel to the dust lane. Numerous globular clusters, each containing up to a million stars, dot the galaxy's outer halo.

The dust lane appears slightly bent compared to the stellar disk. This may be the result of a gravitational interaction with another galaxy in the past. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

Composite-image arithmetic



A CHANCE ALIGNMENT is the main feature of NGC 3314. A face-on spiral galaxy lies precisely in front of another larger, inclined spiral. This lineup provides astronomers with the rare chance to see the dark material in the foreground galaxy silhouetted against the light from the object behind it. NGC 3314 lies about 140 million light-years away in the constellation Hydra. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

Galactic baseline

Astronomers use the Milky Way as the standard and compare all other galaxies' properties (such as size and mass) to it. We know the most about our galaxy, although we haven't seen it from outside. But the Milky Way has surprised us.

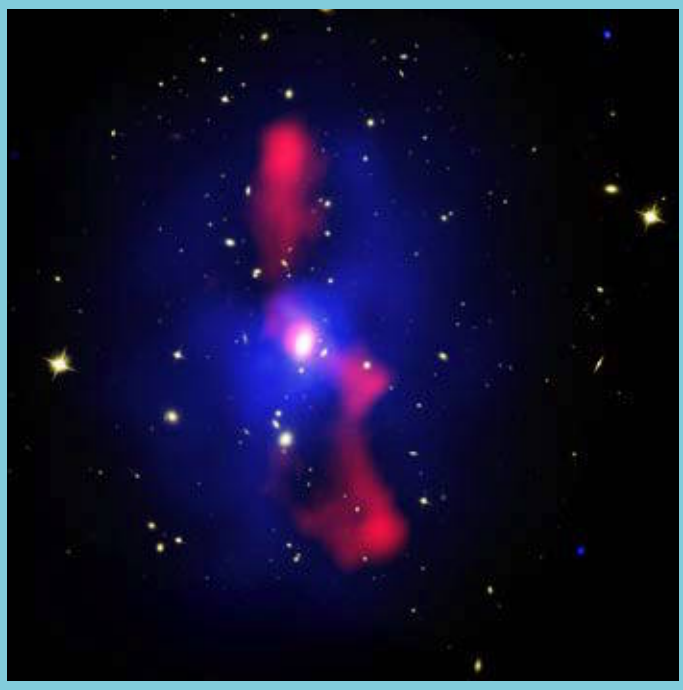
Throughout the 20th century, astronomers classified the Milky Way as a typical spiral galaxy. Recent data from the Spitzer Space Telescope, however, has painted a different picture. In the center of our galaxy lies a large bar of stellar material. Because of intervening dust and gas, this bar is invisible to optical telescopes such as Hubble. The bar's infrared signature, however, penetrates interstellar material, which allowed Spitzer to detect it. So, the Milky Way's current classification is barred spiral.

The Milky Way measures approximately 100,000 light-years across and contains between 200 and 400 billion stars. Our solar system lies roughly 25,000 light-years from the galactic nucleus along the spiral arm designated the Orion Arm. Galaxies are not static objects. Each star, planetary system, or interstellar cloud that a galaxy contains revolves around its center. Our solar system revolves once about the Milky Way's nucleus in 225 million years.

At our galaxy's heart lies a supermassive black hole. Such objects resemble traditional black holes but have masses between hundreds of thousands and billions of solar-masses. Astronomers believe supermassive black holes inhabit the nuclei of most large elliptical and spiral galaxies.

Two large, easily seen satellite galaxies orbit the Milky Way. Observers south of the equator can spot the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC), two irregular galaxies first described by Portuguese explorer Ferdinand Magellan (1480–1521).

The LMC lies in the constellation Dorado 170,000 light-years away. The SMC lies in Tucana 210,000 light-years away. Both galaxies have played important



◄ HOW DO ASTRONOMERS build a composite image? Galaxy cluster MS0735.6+7421 lies about 2.6 billion light-years away in the northern constellation Camelopardalis the Giraffe. The final image combines observations through three telescopes.

Hubble's optical view of the galaxy cluster, image 1, taken by the Advanced Camera for Surveys, shows dozens of galaxies bound together by gravity. Diffuse, hot gas with a temperature of nearly 50,000,000° F permeates the space between the galaxies. The gas emits X rays, seen as blue in image 2 taken with the Chandra X-ray Observatory. The image shows enormous cavities in the gas, each roughly 640,000 light-years in diameter. The cavities contain charged particles gyrating around magnetic field lines and emitting radio waves, shown in the red portion of image 3 taken with the Very Large Array telescope in New Mexico.

The cavities arose from jets of charged particles ejected at nearly light-speed from a supermassive black hole in the nucleus of the central galaxy. The jets displaced more than a trillion solar-masses worth of gas. HUBBLE AND CHANDRA IMAGES: NASA/ESA/CXC/STScI/B. McNAMARA (UNIV. OF WATERLOO); VERY LARGE ARRAY TELESCOPE IMAGE: NRAO/L. BIRZAN AND TEAM (OHIO UNIV.)

▲ THE SOMBRERO GALAXY (M104) is one of the universe's most photogenic galaxies. Thick dust lanes comprising the spiral structure of the galaxy surround its brilliant white, bulbous core. From our perspective, the galaxy appears nearly edge-on. We view it from just 6° north of its equatorial plane.

The Sombrero lies at the southern edge of the rich Virgo cluster of galaxies and is one of the most massive objects in that group, equivalent to 800 billion Suns. The galaxy measures 50,000 light-years across and lies 28 million light-years from Earth. It contains a rich system of globular clusters, estimated at nearly 2,000 — 10 times as many as orbit the Milky Way.

X-ray emission suggests material is falling into M104's compact core, where a billion-solar-mass black hole resides. Measured orbital speeds of stars within the Sombrero confirm this idea.

The Hubble Heritage Team took images through red, green, and blue filters with the Advanced Camera for Surveys to yield this true-color image. The team took six pictures of M104 and then stitched them together to create the final composite. NASA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

roles in helping astronomers understand the universe. In 1912, American astronomer Henrietta Leavitt (1868–1921) discovered a relationship between the pulsation period (how long it takes a star to vary its brightness) and the luminosity of Cepheid variable stars in the Magellanic Clouds.

Today, Hubble continues to observe these two galaxies. Within both objects, astronomers have studied emission and planetary nebulae, supernova remnants, starburst clusters, and massive, hot stars. Each image forms part of the puzzle that helps explain the Magellanic Clouds.

Safety in numbers

Galaxies do not spread uniformly throughout the universe but congregate into groups, clusters, and superclusters. The Milky Way belongs to (and is one of the largest members of) the Local Group, a collection of about 40 galaxies that also contains the Andromeda Galaxy (M31) and the Pinwheel Galaxy (M33). Galaxy groups contain up to 50 galaxies.

The next largest agglomeration of galaxies forms a cluster. Galaxy clusters contain up to several thousand galaxies and come in two types. Regular galaxy clusters have a spherical shape. Astronomers subdivide regular clusters according to their richness, a measurement that depends on the number of member galaxies within about 5 million light-years of the cluster's center. The average regular galaxy cluster contains about 10^{15} solar-masses. One giant elliptical often dominates most small galaxy clusters.

Irregular galaxy clusters come in different shapes and densities. They have no well-defined center and are only 1⁄10 to 1⁄1,000 as rich as regular clusters.

Hubble has imaged mature galaxies in relatively young galaxy clusters. In one instance, Hubble imaged a galaxy cluster as it appeared when the universe

► **FACE-ON GALAXY** NGC 1309, 100 million light-years away in the constellation Eridanus, looks like a child's pinwheel ready to spin. Bright blue areas of star formation trace its spiral arms, while darker dust lanes follow the spiral structure into a yellowish nucleus of old stars.

NGC 1309 is helping astronomers measure the universe's expansion rate more accurately. NGC 1309 was home to supernova SN 2002fk, whose light reached Earth in September 2002. This type Ia supernova resulted from a white-dwarf star gathering matter from its companion in a binary star system.

When the white dwarf collected enough mass, the star detonated, becoming the brightest object in the galaxy for several weeks. Astronomers use nearby type Ia supernovae as "standard candles" to calibrate distance.

By comparing nearby type Ia supernovae to more distant ones, they can determine how the universe is expanding. This method works only if the distance to the host galaxies is well known.

Hubble's Advanced Camera for Surveys helped astronomers accurately determine the distance to NGC 1309 by measuring the light output of a type of variable star called a Cepheid (named for their prototype in Cepheus). Cepheids vary regularly in brightness at a rate directly related to their luminosity. By comparing their rates with how bright they appear, astronomers can deduce their distances. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)/A. RIESS (STScI)

▲ **COLLIDING GALAXIES** in Canis Major fling out stars and gas into long streamers stretching 100,000 light-years. The larger and more massive galaxy is NGC 2207 (left), and the smaller one is IC 2163. Strong tidal forces from NGC 2207 have distorted the shape of IC 2163 as it swings past its companion in a counterclockwise direction.

The large concentrations of gas and dust in both galaxies may well erupt into regions of active star formation in the near future. Astronomers think the two galaxies made their closest approach to each other 40 million years ago.

IC 2163 does not have enough energy to escape the gravitational pull of NGC 2207, so, at some future date, it will swing past the larger galaxy again. Billions of years from now, this pair will merge into a single, more massive galaxy.

To obtain this image, astronomers combined three WFPC2 exposures, totaling 4.5 hours.

NASA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

was only 5 billion years old. The presence of well-developed galaxies within the cluster proved galaxy formation occurred shortly after the Big Bang.

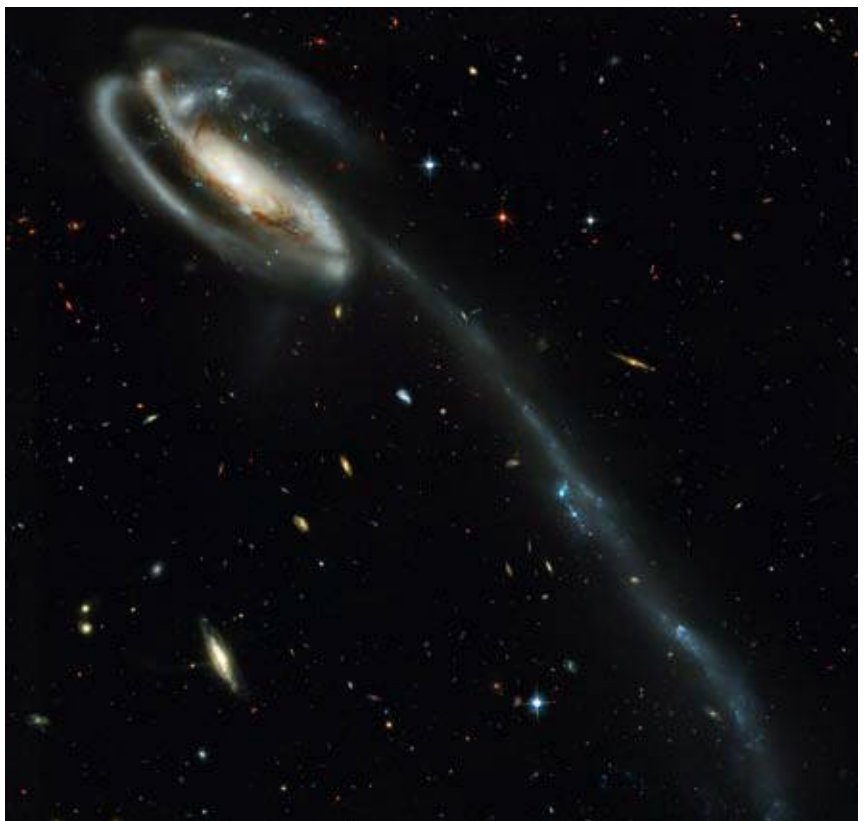
Galaxy superclusters generally comprise chains of about a dozen galaxy clusters. Our local supercluster (called the Virgo supercluster) is smaller than most superclusters. It measures roughly 50 million light-years across.

The next nearest supercluster to ours contains two parts. Astronomers call it the Hydra-Centaurus supercluster. The two main superclusters, each containing several galaxy clusters, lie approximately 200 million light-years away.

The largest nearby supercluster of galaxies is the Perseus-Pisces supercluster. This incredible collection of galaxies lies 250 million light-years away. Even at that distance, however, this group's apparent size is greater than 40°.

The Horologium supercluster is another massive collection of galaxies that lies nearly a billion light-years away, toward the southern constellation Horologium the Clock. The cluster measures more than 500 million light-years across and contains roughly 30,000 giant galaxies and 300,000 dwarf galaxies.

Hubble continues to photograph our universe's galaxies. Each image adds a piece to the cosmic puzzle as astronomers move closer to understanding how galaxies formed and how they continue to evolve. H



◄ **THE TADPOLE GALAXY** (UGC 10214) looks odd, with a long stellar streamer trailing behind it. A small interloper distorted its shape sometime in the past. This blue, compact galaxy is visible in the upper-left corner of the larger Tadpole. Strong gravitational forces from the interaction created the long "tail" of stars and gas stretching out more than 280,000 light-years.

In this Advanced Camera for Surveys image, astronomers see numerous young blue stars and star clusters in both the spiral arms and in the tail. Each of these clusters contains about a million stars. They appear blue because they contain massive stars 10 times hotter and a million times brighter than our Sun.

The Tadpole lies about 420 million light-years away in the constellation Draco. NASA/THE ACS SCIENCE TEAM (H. FORD, G. ILLINGWORTH, M. CLAMPIN, G. HARTIG, T. ALLEN, K. ANDERSON, F. BARTKO, N. BENITEZ, J. BLAKESLEE, R. BOUWENS, T. BROADHURST, R. BROWN, C. BURROWS, D. CAMPBELL, E. CHENG, N. CROSS, P. FELDMAN, M. FRANX, D. GOLIMOWSKI, C. GRONWALL, R. KIMBLE, J. KRIST, M. LESSER, D. MAGEE, A. MARTEL, W. J. MCCANN, G. MEURER, G. MILEY, M. POSTMAN, P. ROSATI, M. SIRIANNI, W. SPARKS, P. SULLIVAN, H. TRAN, Z. TSVETANOV, R. WHITE AND R. WOODRUFF)/ESA

Ring in the new

Cassiopeia A is the youngest known supernova remnant in the Milky Way. It received its name in 1947, when British radio astronomers mapped the brightest radio source within the northern constellation Cassiopeia the Queen. The gaseous debris we see glows because the supernova's shock wave generated heat when it passed by. The colors give astronomers clues about the expanding cloud's chemical composition: Green filaments are rich in oxygen; red and purple contain sulfur; and the blue comes primarily from hydrogen and nitrogen. Cassiopeia A lies approximately 10,000 light-years away. This image is a composite of 18 taken in March and December 2004 by Hubble's Advanced Camera for Surveys. Total exposure time equaled nearly 200,000 seconds (2.3 days). The field of view spans some 25 light-years. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

To the edge of

Hubble has looked to the distant past to tell us what our future holds.

By far, today's most popular science topic is cosmology — the branch of astronomy that deals with the origin, structure, and fate of the universe. Nothing captures people's imaginations like cosmology, and no telescope has given us more dazzling space discoveries than Hubble.

Unfortunately, today's cosmologists are in a bit of a pickle: They don't know what most of the universe is made of. What we see (that is, ordinary matter that gives off or reflects light) accounts for only 4 percent of the universe, and only 0.4 percent is bright stuff like stars.

All the rest, cosmologists say, comprises dark matter (about 23 percent) and dark energy (about 73 percent). That's good to know, except for the fact that astronomers cannot describe the true nature of either of these concepts. Scientists can infer the existence of these two components, however, by the effect each has on its surroundings.

space and time

▲ EINSTEIN'S CROSS (G2237+0305) is a gravitational lens within the boundaries of the constellation Pegasus. Gravitational lensing occurs when light from a distant source passes close to a massive foreground object.

Hubble's Faint Object Camera shows four images of a single distant quasar. The quasar lies roughly 8 billion light-years away, whereas the lensing galaxy, at a distance of 400 million light-years, is 20 times closer.

The light from the quasar bends because of the galaxy's gravitational field. This bending produces the four bright outer images. The galaxy's bright core is the diffuse central object.

Gravitational lenses are useful probes of many types of phenomena that occur in the cosmos. For example, astronomers can "weigh" the foreground galaxy by measuring the relative positions and the brightnesses of the different images of the quasar. NASA/ESA

◄ THIS POPULATION of faint blue galaxies is one of Hubble's deepest images. Their distances range from 3 to 8 billion light-years. Deciphering the formation and evolution of these blue dwarf galaxies may provide new clues to understanding the process of galaxy evolution, including the formation of the Milky Way.

Most of these objects do not resemble galaxies today. Instead, their variety of shapes suggests past galaxy collisions and other interactions were more common.

This true-color image combines separate exposures taken in blue, green, and far-red light by Hubble's Wide Field and Planetary Camera 2. It required a total of 48 orbits around Earth (amounting to roughly 1 day of exposure time) and shows objects at 30th magnitude — about 4 billion times fainter than the unaided eye can see. The image covers an area of sky in Hercules only one-tenth the diameter of the Full Moon. ROGIER WINDHORST AND SIMON DRIVER (ARIZONA STATE UNIV.)/BILL KEEL (UNIV. OF ALABAMA)/NASA

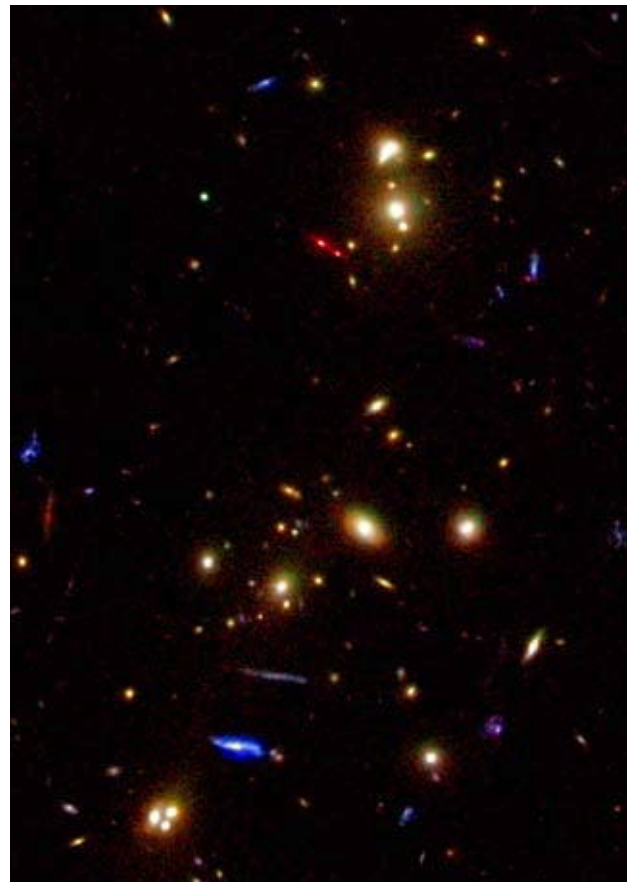
The dark side, part 1

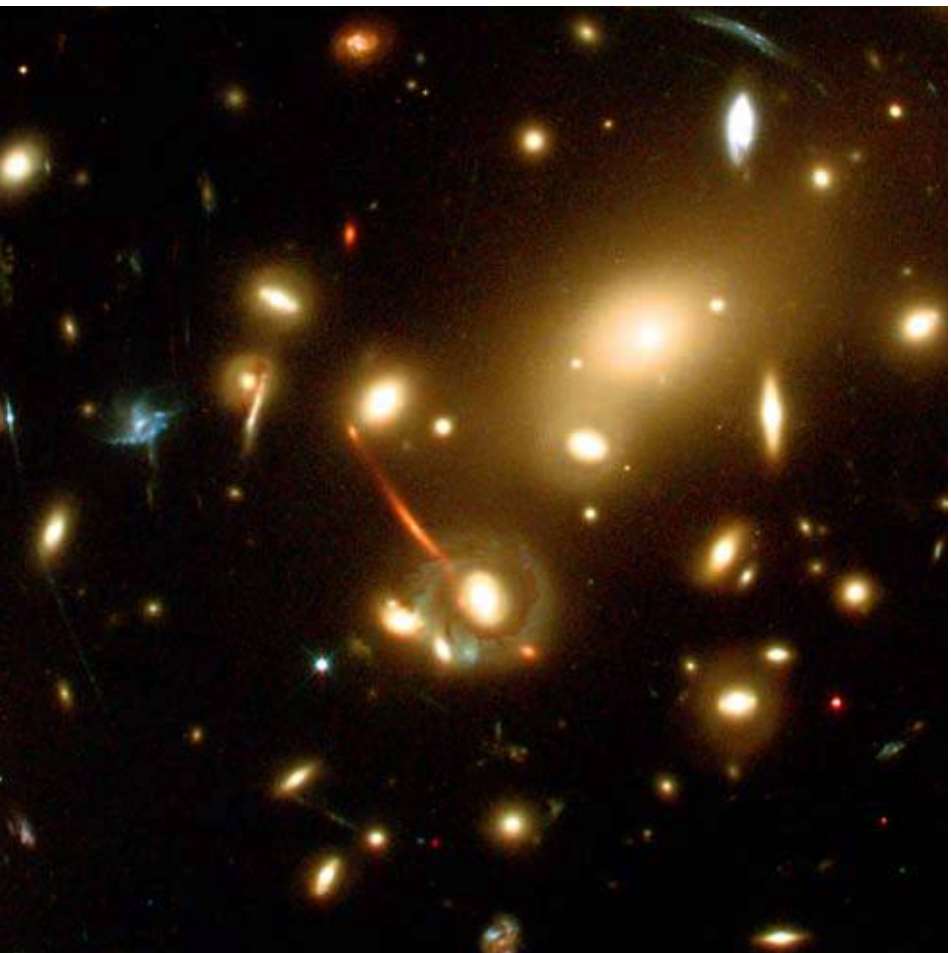
Dark matter emits no energy we can detect, but astronomers studying galaxies and galaxy clusters see its effects. All galaxies spin. Astronomers, however, cannot account for a galaxy's rotational velocity based on calculations that just use the galaxy's visible mass (stars, star clusters, and nebulae). Galaxies remain intact only if more mass — and in most cases, a lot more than astronomers observe — exists. Because this mass remains undetected visually, it's called dark matter.

Astronomers theorize dark matter causes other effects: Galaxy clusters don't contain enough visible mass to hold themselves together. Without some material that creates a large gravitational attraction, galaxy clusters would disperse quickly. And the Big Bang itself may not have created our universe without a large quantity of dark matter.

In August 2006, astronomers found the first direct proof for dark matter's existence. Using Hubble and the Chandra X-ray Telescope, they imaged galaxy cluster 1E 0657–556, also known as the Bullet Cluster. The only way astronomers can explain how material escapes from this object is with dark matter's influence. In early 2007, a team of astronomers created a three-dimensional map of the large-scale distribution of dark matter in the universe.

The new map provides the best evidence that normal matter (galaxies) accumulates along the densest concentrations of dark matter. The map shows dark matter as a loose network of filaments that grew over time and became increasingly clumpy as it collapsed under gravity's influence. Astronomers constructed the dark-matter map by measuring the shapes of half a million distant galaxies.





◄ **GALAXY CLUSTER** Abell 2218 in the constellation Draco acts like a lens, magnifying all of the galaxies behind the cluster's core. The lensed galaxies, which lie 5 to 10 times Abell 2218's distance, stretch along the cluster's center, and some of them are multiple images, which appear as a pair of images with a third, generally fainter, counter-image.

The colors of the lensed galaxies are a function of their distances and types. The orange arc is a nearby elliptical galaxy. The blue arcs are star-forming galaxies at intermediate distances.

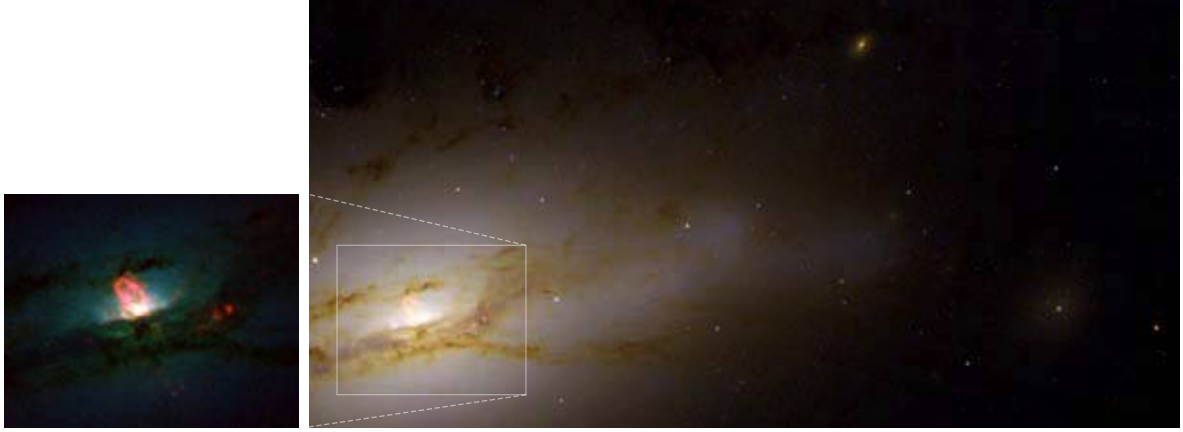
The red pair is a newly discovered, distant star-forming galaxy. The lensed galaxies are so numerous because the image shows the "saddle" region between two mass clumps where the magnification is quite large.

This image marked the first time astronomers could view the internal color structure of distant galaxies. ESA/NASA/J.-P. KNEIB (CALTECH/OBSERVATOIRE MIDI-PYRENEES)/R. ELLIS (CALTECH)

▲ **THE LYNX CLUSTER** of galaxies shows the doubled image of the red Lynx arc (just above center). The mysterious arc is a distant supercluster of stars lying far behind the galaxy cluster in the northern constellation Lynx.

The arc is the stretched and magnified image of a star-forming region 12 billion light-years away. This remote object existed when the universe was less than 2 billion years old.

Astronomers discovered this object as a result of a systematic study of distant galaxy clusters carried out with major X-ray, optical, and infrared telescopes, including Hubble, ROSAT, and the Kecks. The Hubble image, taken in deep-red light with the WFPC-2, was color-enhanced using six images taken with the Mayall 4-meter Telescope at the National Optical Astronomy Observatory's Kitt Peak Observatory in Arizona. ESA/NASA/ROBERT A. E. FOSBURY (ESA/SPACE TELESCOPE-EUROPEAN COORDINATING FACILITY, GERMANY)/NOAO

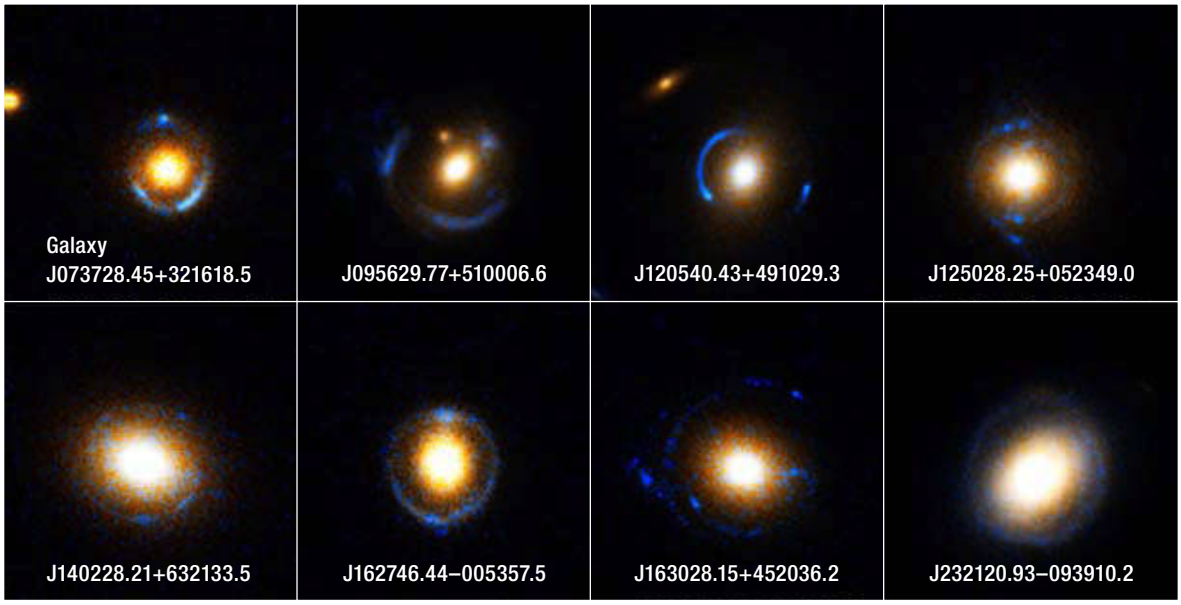


◄ **PECULIAR GALAXY** NGC 4438 contains a monstrous black hole that is blowing huge bubbles of hot gas into space. NGC 4438 lies in the Virgo cluster of galaxies, approximately 50 million light-years from Earth.

These Hubble images of the galaxy's central region show one of the bubbles rising from a dark dust band. The right image shows a wide view of the galaxy.

A black hole feeds itself with material swirling around it in an accretion disk (the white region). Some of this material spews from the disk in opposite directions. These jets eventually slam into walls of slow-moving gas.

The bubble appears brighter on one side of the galaxy's center because the jet smashed into a denser gas region there. Hubble's Wide Field and Planetary Camera 2 took both pictures March 24, 1999. Astronomers used false colors to enhance details of the bubbles. Red regions denote the hot gas. NASA/JEFFREY KENNEY AND ELIZABETH YALE (YALE UNIV.)



▲ **THIN BLUE** bull's-eye patterns in these eight Hubble images float over reddish-white blobs — giant elliptical galaxies roughly 2 to 4 billion light-years away.

The bull's-eye patterns are so-called Einstein rings, which are the most elegant manifestation of the lensing phenomenon. Einstein rings form only when two galaxies are aligned, one behind the other, from our point of view.

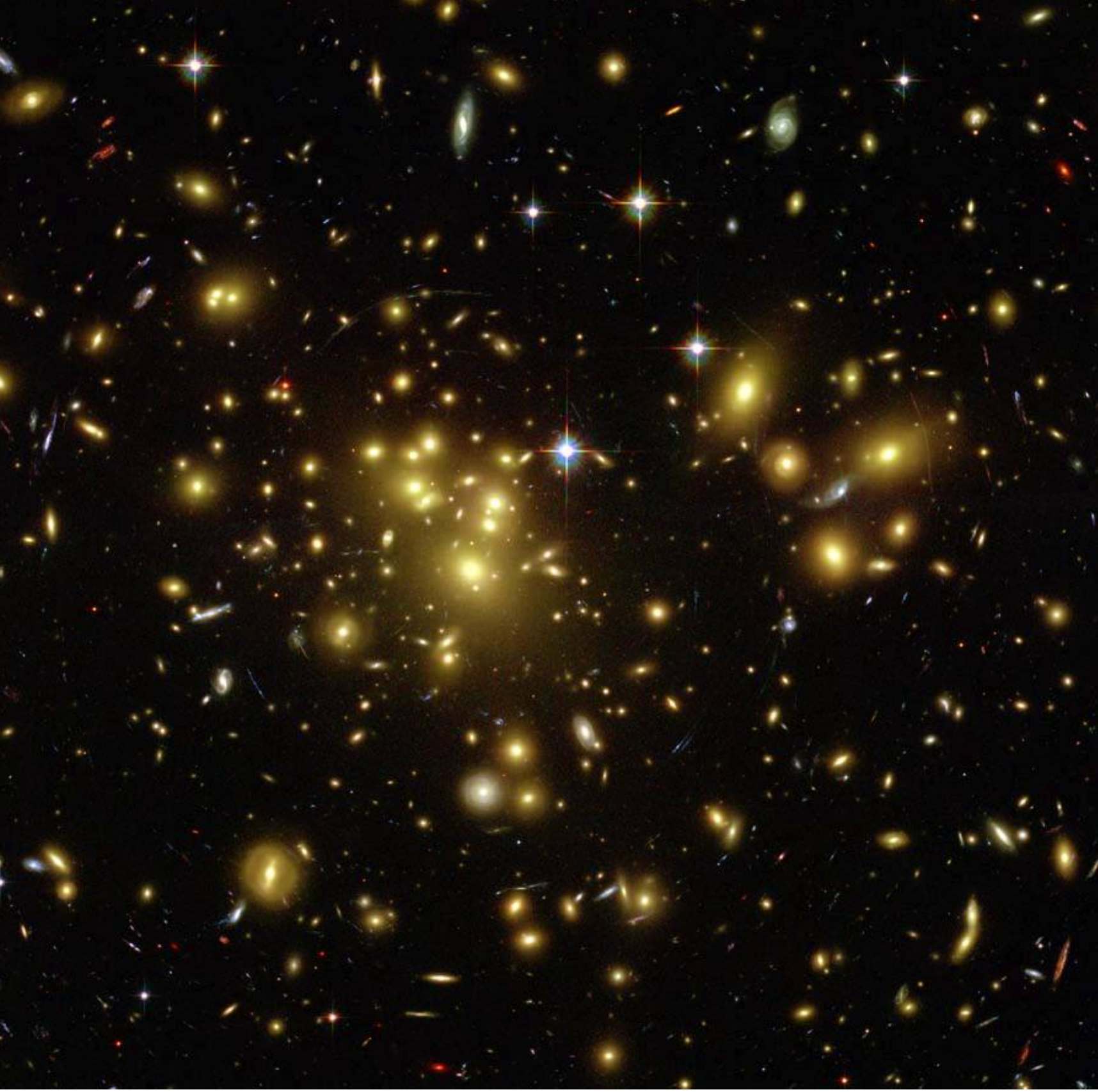
Hubble's Advanced Camera for Surveys took the images between August 2004 and March 2005 as part of the Sloan Lens ACS (or SLACS) Survey. This survey searched about 150 galaxies for gravitational lenses. The survey netted 19 new gravitational lenses and also identified eight new Einstein rings. Astronomers had observed only three such rings previously in visible light. NASA/ESA/THE SLACS SURVEY TEAM: A. BOLTON (HARVARD-SMITHSONIAN CfA), S. BURLES (MIT), L. KOOPMANS (KAPTEYN), T. TREU (UCSB), AND L. MOUSTAKAS (JPL/CALTECH)

The dark side, part 2

If you thought dark matter was strange, hang on to your hat. Dark energy is a theoretical construct intended to explain an observation made in the late 1990s. Two research teams, the Supernova Cosmology Project at the University of California's Lawrence Berkeley Laboratory, and the High-Z Supernova Search Team, looked at a type of supernova and how its emitted light changed over time. Based on their observations, the teams concluded the universe's expansion is accelerating.

The researchers defined a quantity — dark energy — that permeates the universe and exerts a pressure opposite that of gravity. Dark energy's exact nature, however, remains a mystery. Besides believing it exists everywhere, astronomers think dark energy is diffuse and interacts only through gravity — not through the other fundamental forces (electromagnetism and the strong and weak nuclear forces). Because it is so meager (estimates put its density at 10^{-29} grams per cubic centimeter), dark energy will be difficult to detect.

Astronomers using Hubble data estimate the universe's expansion began to accelerate roughly 9 billion years ago. Before then, the combination of visible and dark matter exerted enough gravity to decelerate the expansion. As the cosmos expanded, however, matter's density decreased, while dark energy's density remained the same, according to the prevailing theory. Nine billion years ago, dark energy's "push" overcame gravity's "pull," so we live in a universe whose expansion is accelerating.



▲ **ABELL 1689** is a massive cluster of yellow galaxies, seemingly caught in a red-and-blue spider web of eerily distorted background galaxies. To make this image, Hubble peered through the center of Abell 1689, one of the most massive galaxy clusters known.

The gravity of the cluster's trillion stars, plus dark matter, acts as a 2-million-light-year-wide gravitational lens, which bends the light of galaxies located behind it. The faintest objects lie 13 billion light-years away.

The Advanced Camera for Surveys picture shows 10 times more arcs than a ground-based telescope would reveal. Interspersed with the foreground cluster are thousands of lensed images of background galaxies.

Astronomers hope images like this will shed light on galaxy evolution, the curvature of space, and the mystery of dark matter. Each image combines visible-light and near-infrared exposures taken in June 2002.

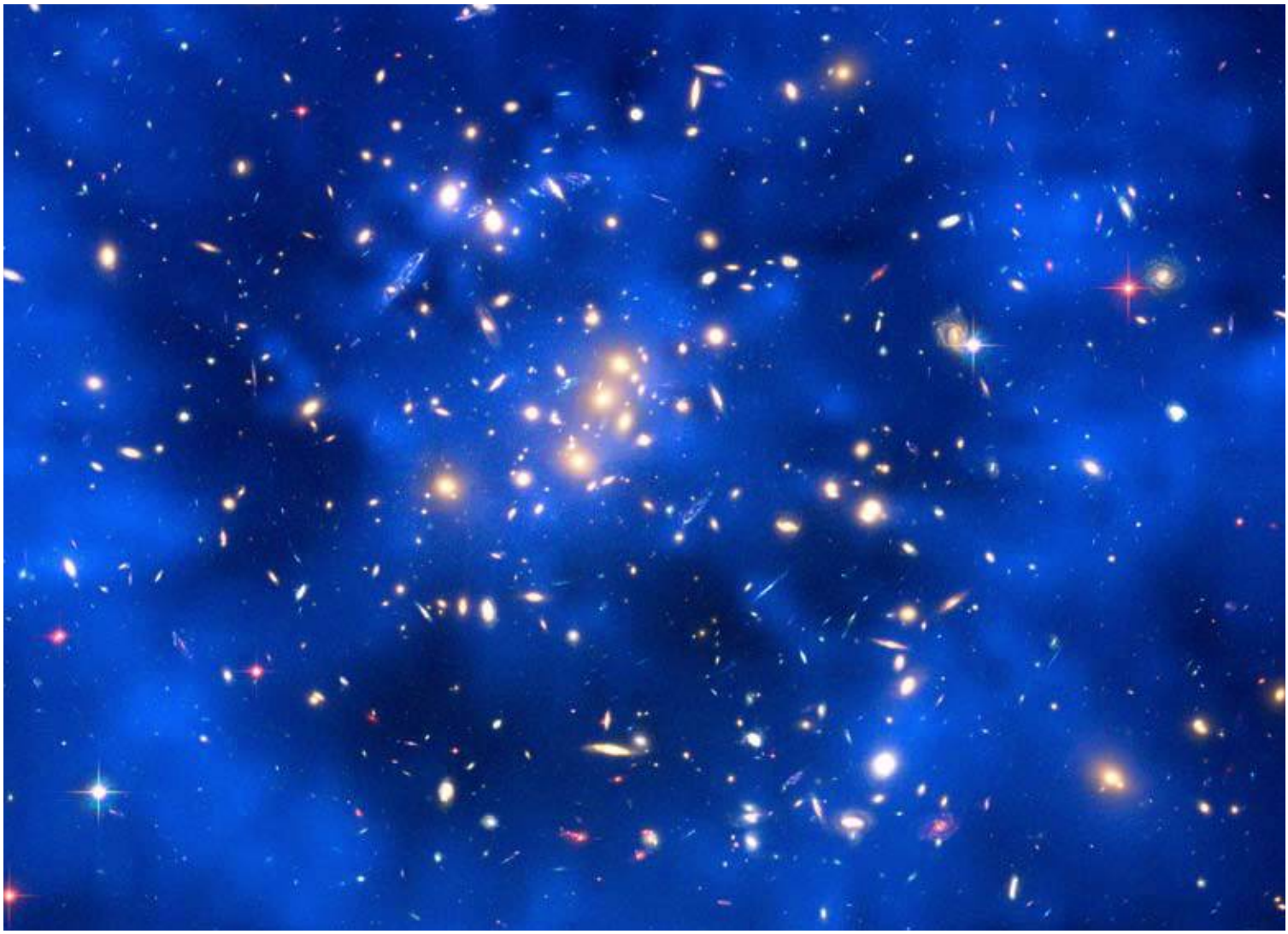
NASA/N. BENITEZ (JHU)/T. BROADHURST (RACAH INST. OF PHYSICS/THE HEBREW UNIV.)/H. FORD (JHU)/M. CLAMPIN AND G. HARTIG (STScI)/G. ILLINGWORTH (UCO/LICK OBSERVATORY)/THE ACS SCIENCE TEAM/ESA

Natural lenses

A strange phenomenon astronomers can observe is gravitational lensing. This effect occurs when a massive object (such as a galaxy or galaxy cluster) bends the light from a more distant object that lies behind it from our point of view.

Hubble has captured several instances of gravitational lensing. In a few cases, such as Einstein's Cross, a single object transforms into many copies of itself. Other gravitational lenses form arcs of distant objects.

Gravitational lensing is a prediction of Einstein's theory of relativity. The first test of a massive object bending light occurred during a total solar eclipse in 1919. Astronomers observed two stars close to the Sun that were not in their normal positions — exactly as predicted by relativity theory.

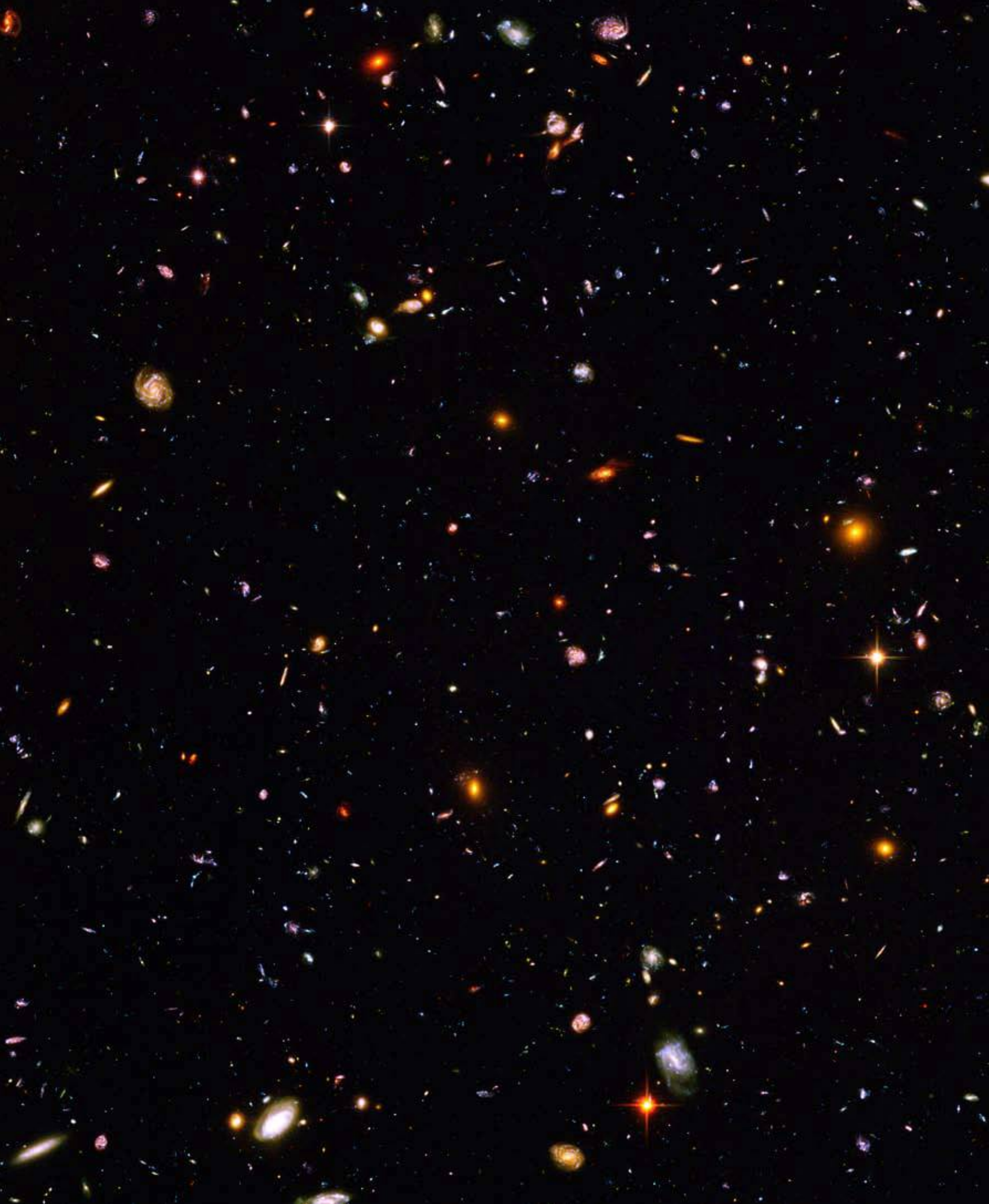


▲ **GALAXY CLUSTER** Cl 0024+17 provides the strongest evidence yet that dark matter exists. Dark matter, which astronomers cannot observe directly, reveals its existence by interacting gravitationally with light.

In the case of Cl 0024+17, researchers mapped the dark matter so it appears as a bluish, ghostly ring superimposed on a Hubble image of the cluster. The ring measures 2.6 million light-years across. Cl 0024+17 lies approximately 5 billion light-years from Earth in the constellation Pisces.

Astronomers believe the dark-matter ring formed when two clusters of galaxies collided between 1 and 2 billion years ago. Hubble's Advanced Camera for Surveys acquired this image, a 14.5-hour composite of many exposures through six filters, in November 2004. The area shown measures approximately 3 arcminutes across.

NASA/ESA/M. J. JEE AND H. FORD (JOHNS HOPKINS UNIV.)



More exotic quarry

Astronomers using Hubble have uncovered characteristics of our universe they don't yet understand. For example, one research team imaged a population of faint blue galaxies 3 to 8 billion light-years away that turned out to be the universe's most common class of object. Further study may help explain the process of galaxy evolution, including the formation of our Milky Way Galaxy.

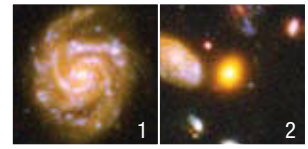
Other scientists concentrate Hubble's instruments on galaxies to gather evidence of supermassive black holes at their centers. Such objects — with masses as large as hundreds of billions of times greater than the Sun — probably dominate the hearts of all large galaxies. Although no telescope can image a black hole directly, Hubble can search for telltale signs, such as large clouds of gas glowing with specific energies.

Galaxies themselves present a problem for astronomers, who don't know what processes caused galaxies to form or evolve. In fact, scientists have a better overall picture of the universe's birth and evolution than that of galaxies'. By using Hubble, they can look back in time nearly to the Big Bang with unprecedented clarity. Galaxies that appear in such images represent the youngest such objects ever seen. Cosmologists currently are comparing those distant objects with nearby galaxies in hopes of solving the galaxy-formation puzzle.

◄ **THE HUBBLE** Ultra Deep Field (HUDF) represents a picture of the early universe. The image reveals the first galaxies to emerge from the so-called Dark Ages, a time shortly after the Big Bang when the first stars reheated the cold, dark universe.

This view is a combination of two separate images taken by Hubble's Advanced Camera for Surveys and the Near Infrared Camera and Multi-object Spectrometer. Both images reveal galaxies too faint to be seen by ground-based telescopes, or even in the two Hubble Deep Fields, taken in 1995 and 1998.

The 800 exposures amounted to about 1 million seconds, or 11.3 days of viewing time. The average exposure time was 21 minutes. The image shows about 10,000 galaxies. The patch of sky in the southern constellation Fornax is so tiny, it would take about 50 Ultra Deep Fields to cover the Full Moon. It took Hubble 400 Earth orbits to complete the observations. NASA/ESA/S. BECKWITH (STScI)/THE HUDF TEAM



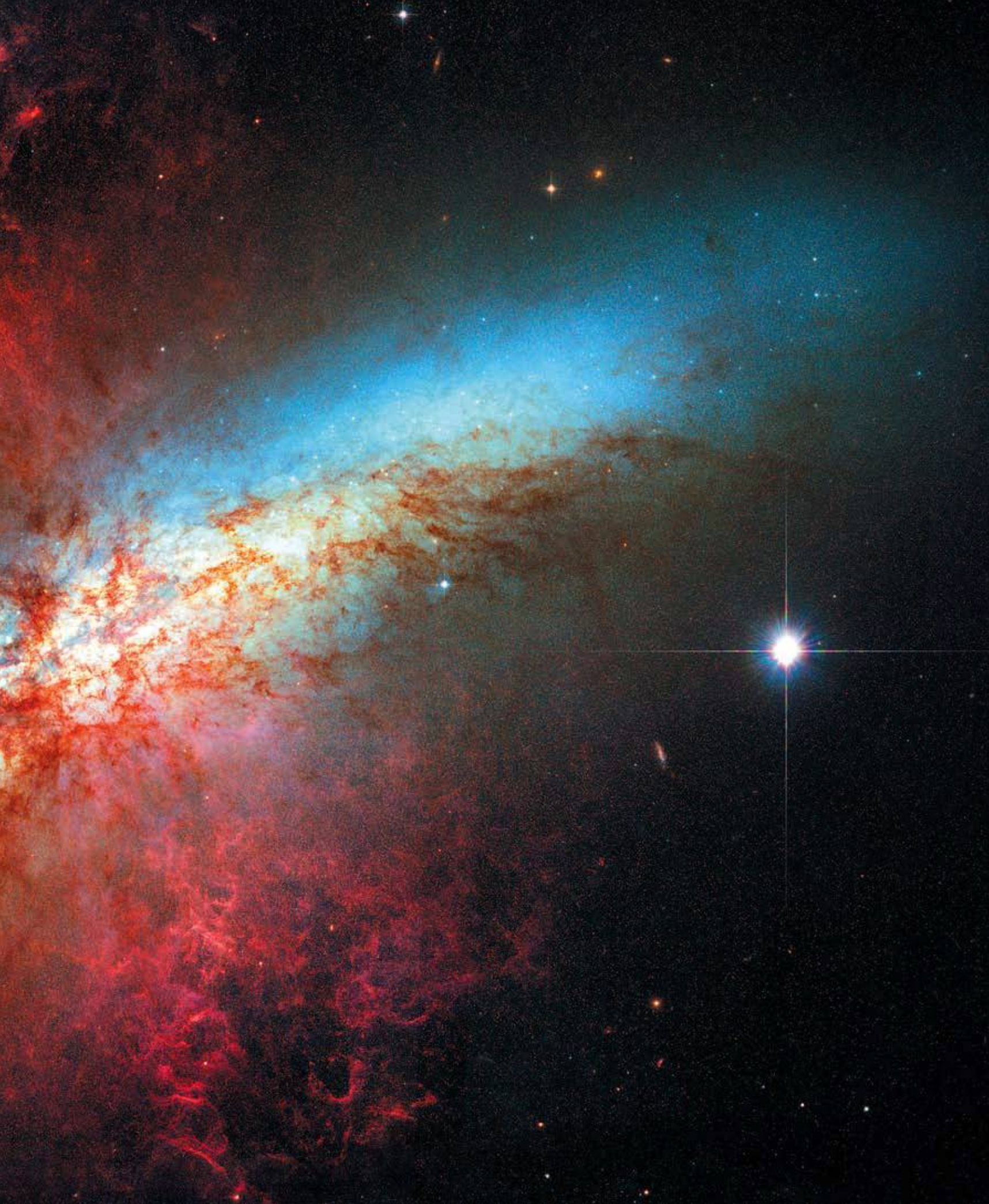
▲ **OBJECTS** within the Hubble Ultra Deep Field range from stars in our own neighborhood to the most distant galaxy with a directly measured redshift (6.7). Astronomers express distance in the far universe using redshift because it's the most easily determined distance indicator. The preferred alternative is to express extreme distances in terms of the universe's age.

UDF 7556 (1), a spiral galaxy at redshift 0.89 (6.1 billion years after the Big Bang) is making a lot of stars.

UDF 8316 (2), centered in the image, is an elliptical galaxy at redshift 0.62. Its light took 5.8 billion years to reach us. NASA/ESA/STScI/S. BECKWITH/SANGEETA MALHOTRA

Bursting on the scene

This image of the Cigar Galaxy (M82), a starburst galaxy in the constellation Ursa Major the Great Bear, commemorated Hubble's 16th year of operation. This mosaic image is the sharpest wide-angle view ever obtained of M82. The galaxy is remarkable for its bright blue disk of intense star formation, webs of massive cloud-like star clusters, and fire-like plumes of glowing hydrogen blasting out of its central regions. Hubble's Advanced Camera for Surveys acquired 13.7 hours of exposures March 27–29, 2006, to produce this image. The Cigar Galaxy lies approximately 12 million light-years away. This image spans 28,000 light-years. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



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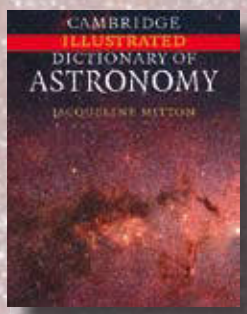

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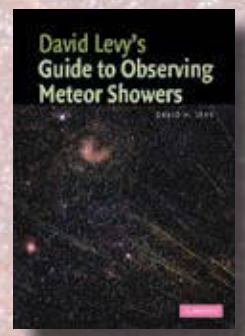

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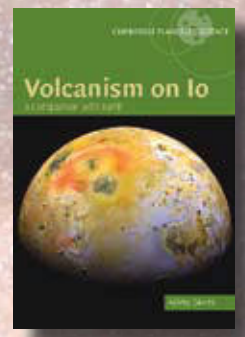

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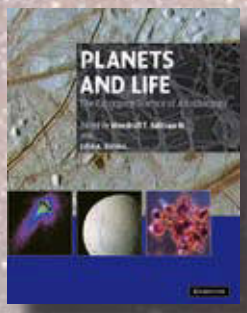

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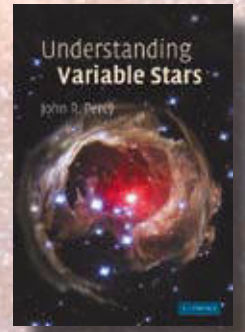

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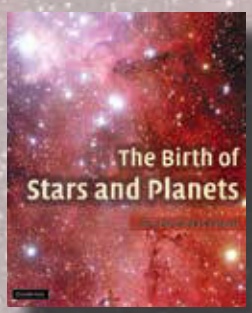

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